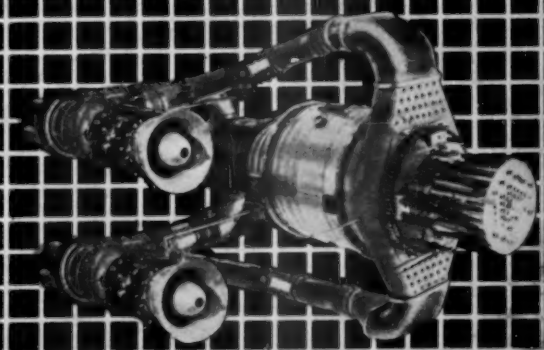
JANUARY 1961

NUCLEONICS

ATOMIC POWER • NUCLEAR ENGINEERING • APPLIED RADIATION

Nuclear Propulsion for Aircraft

Technical achievements of the direct-cycle program



. . . page 45

A McGraw-Hill Publication • One Dollar

SPECIAL

Discount

OFFER!

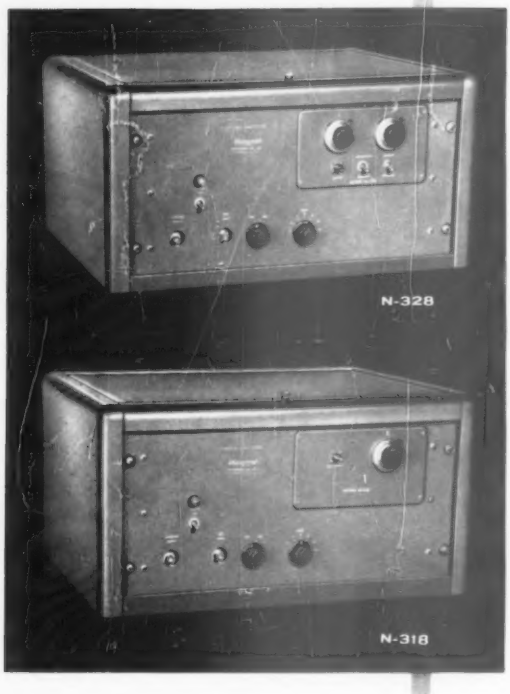
In order to introduce these amplifiers to major laboratories, a special 10% discount is available on any order of 5 or more units if placed before March 1.

HAMNER

A-8 DESIGN
ULTRA HIGH SPEED, NON-OVERLOAD
LINEAR AMPLIFIERS

Unexcelled A-8 Characteristics . . . PLUS

- OUTPUT FOR FAST COINCIDENCE WORK
- OPTIONAL PICK-OFF FOR 40 mμs RANGE COINCIDENCE
- YOUR CHOICE OF DISCRIMINATORS



The A-8 Design Amplifier has found wide usage in nuclear physics laboratories where one or more of the following three conditions exist:

1. Very large overload signals will be present.
2. Counting rates up to 250kc will be present.
3. It is required to do medium-fast coincidence work on pulses having slow risetimes.

In these three areas, the A-8 design represents a great improvement over previous units.

These results are achieved through the use of double differentiation with two delay lines, thus providing for fast baseline recovery even under high-duty cycle operation. Overload performance is enhanced by preventing the Amplifier from overloading before differentiation and by not allowing overload to occur inside a feedback loop.

N-308
AMPLIFIER ONLY

Maximum Gain: 7000 in main Amplifier (additional gain of 1, 3 or 10 in Pre-Amp).

Gain Stability: 0.25% day.

Risetime: About 0.2 μs.

Linearity: 0.1% Integral Linearity, 3-100 volts into 10K or greater load.

Overload Recovery: About 8 μs for 4000 times overload.

Maximum Counting Rate: About 250,000 CPS.

N-318
AMPLIFIER WITH INTEGRAL DISCRIMINATOR

Amplifier Section: See details on N-308.

Discriminator Section: This Discriminator is based on the P. R. Bell Design.

Range: 4-100 volts by 10-turn helipot.

Linearity: Better than 0.5%, 3-100 volts.

Stability: Better than 50 mv day.

Resolving Time: About 1.2 μs.

Output Pulse: 1 μs wide, -50 volts high into 10K load.

N-328
AMPLIFIER WITH PULSE-HEIGHT ANALYZER

Amplifier Section: See details on N-308.

Output Pulse Height: (25 volts, positive or negative by switch.)

Baseline:
Control—By 10-turn helipot.
Range—3-100 volts by 10-turn helipot.
Linearity—0.1%, 3-100 volts.
Stability—Better than 50 mv day.

Window:
Control—By 10-turn helipot.
Width—0-10 volts by 10-turn helipot (0-20, 30, 40 or 50 volts at slight extra cost).

N-670 COINCIDENCE PICKOFF. In Coincidence Work, the time of the pulse zero crossover is largely independent of pulse-height. For this reason, it is well related in time to the event causing the pulse and is useful for coincidence studies. Coincidence resolving times of less than 50 mμs can be successfully used with Sodium Iodide. The N-670 is an optional sub-chassis which detects the zero crossing and presents an output for coincidence work.

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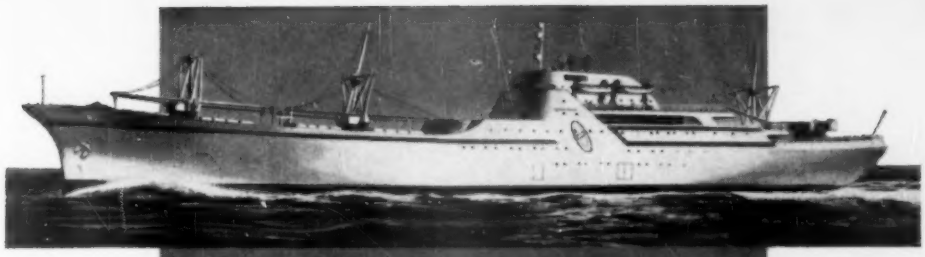
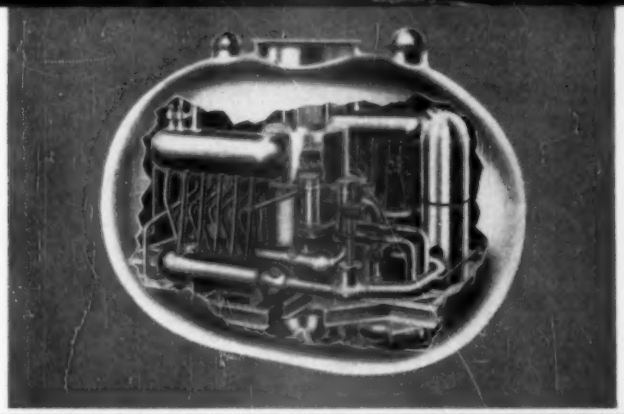
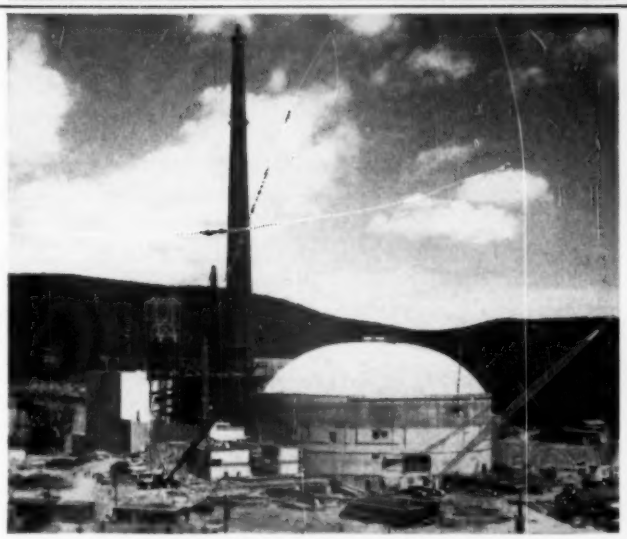




N. S. SAVANNAH . . . forerunner of a nuclear-powered merchant fleet, the Savannah's Pressurized Water Reactor (shown) was designed and fabricated by Babcock & Wilcox.



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Major experience with the Pressurized Water Reactor system has provided The Babcock & Wilcox Company with important data in the search for economic application of nuclear energy.

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NUCLEAR POWER APPLICATIONS

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	Cladding Materials Al Nb SS Be Zr	Pellets in Tubing SS Zr Al	Fuel and Fuel Alloys U-Zr U-Nb U-Al U-Mo U,Th	Fuel Dispersions and Ceramics UC UO_2-SS U_3O_8-Al UO_2 in graphite ThO_2 in graphite	Control Materials B-Al B-SS B_4C-Zr Hf
PRODUCTS					
Castings	√		√		
Clad Materials	√		√	√	√
Control Rods					√
Dispersions				√	√
Fabricated Assemblies	√	√	√	√	√
Fabricated Shapes	√		√	√	√
Foil	√		√		√
Fuel Elements	√	√	√	√	
Fuel Rods		√	√	√	
Poison Strips					√
Tubing	√				
Wire	√		√	√	
PRODUCTION SERVICES					
Annealing and Heat Treating	√		√		√
Assembly	√	√	√	√	√
Brazing	√	√	√		
Casting	√		√		
Cladding	√	√	√		√
Chemical Milling	√		√		√
Extrusion	√		√		
Machining	√	√	√	√	√
Materials Research	√	√	√	√	√
Rolling	√		√	√	√
Vapor Blasting	√		√	√	√
Welding	√	√	√		√
TESTING SERVICES					
Autoclaving	√	√	√	√	√
Chemical Analysis	√	√	√	√	√
Isotopic Analysis			√	√	
Metallography	√	√	√	√	√
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NUCLEONICS

APPLIED RADIATION • ATOMIC POWER • NUCLEAR ENGINEERING

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Mössbauer Effect

For some physics that is fun, turn to page 52. You will find that you can now have gamma-ray energy resolution a million times as good as before. Moreover the photons have just the energy of the nuclear transitions they come from; they are not shifted in energy by atomic recoils, and the energy spectrum is not broadened by Doppler shifts of gases nor vibrations of solids.

The narrowing of gamma lines in both emission and absorption comes from an effect named for its discoverer, the Mössbauer effect. When the emitting and absorbing atoms are bound in crystals, it is sometimes possible to make both emission and absorption occur without recoil. Well, not really. We still can't violate conservation of momentum. But if the crystal as a whole recoils and no quanta of vibration energy (phonons) are transmitted to the crystal, recoil energy is negligible; all of the transition energy is taken away by the photon in absorption and given up to the reverse transition in absorption. The applications in physics are already astounding. But the future holds many more.

Fissile or Fissionable?

If it is *fissile* it is also *fissionable* but not necessarily vice versa. This is the logical conclusion that derives from International Standards Organization's proposed new meanings for these two terms. Heretofore *fissionable* in "American-speaking" countries has meant the same thing as *fissile* in "British-speaking" countries. ISO, which set forth the proposal at a meeting in Geneva in June, 1960, is polling its member nations on a proposal to reserve *fissile* for nuclides that fission on the capture of *thermal* neutrons while *fissionable* would apply to any nuclide that can be fissioned by neutrons in the fission spectrum. Thus U^{235}, U^{233} and Pu^{239} are both fissile and fissionable while U^{238}, Th^{232} and Pu^{240} are merely fissionable. This new usage takes its precedent from similar distinctions made in our language. For instance reactor designers would agree there is an important difference between a reactor that is moveable and a reactor that is mobile.

We invite our readers—American, British and those of other nations—to submit their views on these proposals.

Morning Faces

The New York City Board of Education once sent us a superb pictorial essay on its school system and its accomplishments. Amply illustrated with photographs of school children, it bore the title "Morning Faces." We have done a little to brighten our face on the morning of a new year. The changes are subtle—a more open contents page, new-style department heads, a new scheme for labelling continued stories in the back of the book. (We'll be giving you a shortened version of the article title as well as the page it began on rather than the department name as in the past). We have also redone the advertisers index. (Didn't know we had one? . . . It's darn useful . . . see page 115 . . . that's the next-to-the-last page in the magazine, where we intend to keep it.) There'll be further changes as the year progresses. Good morning, readers!

—*The Editors*

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COMING FEATURES

Chemonuclear Reactors
Radioactive Tracers in Oil-Well Logging
Statistical Design of In-Pile Experiments
Yankee Foldout
Elk River Foldout
Components for Nuclear Reactors

Code Development Program

Accurate Predictions of Reactor Characteristics Will Lower Costs

Under a contract with the U. S. Atomic Energy Commission, scientists and engineers at the Nuclear Division of The Martin Company are developing computer codes which will make possible more accurate predictions of vital characteristics of pressurized water reactors during design stages.

The integrated codes will be made available for use throughout the industry in connection with small reactors of special interest to the Army Nuclear Power Program (ANPP).* These will be the successors to such plants as PM-1 and PM-3A, now under construction at Martin-Nuclear.

Use of mathematical codes will lessen the need for extensive and time-consuming physical tests used at present to predict temperature effects, reactivity, power distribution, control requirements, and the lifetime of the reactor as changes are made in the size, shape and material content of the fuel core.

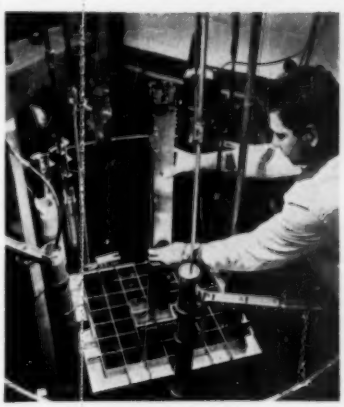
Such codes will be capable of accounting for cell disadvantage factors of fuel and burnable poison and for spatial distribution of fission products as a function of time and operating history. They will also be able to account for such factors as nonuniform fuel loadings and the effects of control rods and lumped burnable poisons.

One of the computers in Martin's digital computation facilities, this one located in Baltimore.

In addition to the mathematical analyses, carried out on high-speed electronic computers, the two-phased ANPP Code Development Program includes critical experiments in the Nuclear Division's test facilities. These experiments provide additional data required to develop the computer codes and check the accuracy of the mathematical solutions.

The code development phase includes the development and analysis of theories, use of Martin machine programs such as SYNFAR, CELCOR, SYBURN and SYD, as well as other existing codes, and the writing of new codes. These codes are linked in a way to permit use of specific blocks as required or use of all parts of the code to determine the total characteristics of a reactor under investigation. Input data comprising basic nuclear constants, plus physical data, are provided on separate tapes. Currently, Martin is using IBM 704 and 709 machines in the development program, with the faster IBM 7090 to be employed shortly. Basic programming is done in FORTRAN (Formula Translation), permitting adaptation to any large scale computing equipment.

The second phase of the program includes several unusual approaches in critical experimentation. Typical is a homogeneous fuel element experiment in which the constituent parts of a conventional (heterogeneous) element are pulverized, blended and dispersed uniformly in plastic. Comparison of results with experiments using the conventional type of element makes it possible to examine the effects of fuel lumping on critical mass and to determine the disadvantage factors.



Experimental physics critical assembly used in the verification of codes developed under the program.

Pulse neutron generator provides a safe, low-level transient test with a minimum of disturbance.

The code development program at Martin has progressed to the point where a pilot code will be made available shortly to the AEC. When the codes are complete, they will enable the prediction of nuclear reactor characteristics to a degree which will all but eliminate the need for extensive critical tests.

** Further inquiries should be directed to USAEC, Division of Reactor Development, Washington 25, D. C.*

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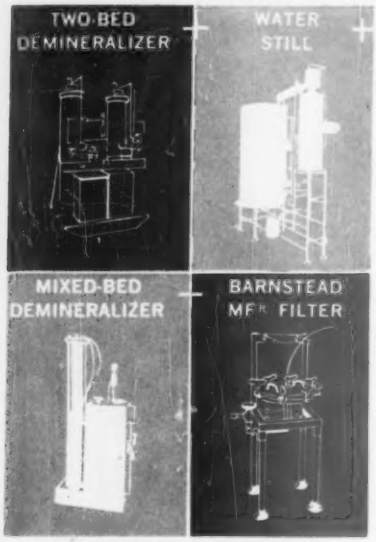

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NUCLEAR REACTIONS

Filmland, USAec

DEAR SIR:

In the guest editorial of the June, 1960 NUCLEONICS ("Educating the Public about Radiation"), Merril Eisenbud states that there are no motion pictures in the AEC film libraries to explain the radiation hazard of the civilian industry to the public.

Your readers may be interested in knowing that such popular-level films as "Living With the Atom," "Living With Radiation," "Atomic Cities" and "Protecting the Atomic Worker"—available at all the Commission's 10 film libraries, nationwide—deal primarily with the matter discussed by Mr. Eisenbud. Other films—of both popular and technical levels—deal in part with the subject.

Film catalogs and films can be obtained from the Commission's Operations Offices or Commission headquarters. Popular and technical films dealing with safety, health physics, waste disposal, etc., are also available.

—DUNCAN CLARK, Director
Office of Public Information
U. S. Atomic Energy Commission
Washington 25, D. C.

DEAR SIR:

The editorial by Merril Eisenbud, while of extreme interest to workers concerned with this problem, contains certain disputable statements.

In his opening paragraph, Mr. Eisenbud says: "A lack of perspective can be found everywhere, not only in the population as a whole, but among statesmen, scientists and writers." This is too broad a statement; it can be said, however, that there is a certain amount of honest disagreement among even well-educated scientists.

"Some feel," Mr. Eisenbud writes, "that the nuclear industry is growing at so great a rate that the country is unable to deal competently with the problems created." Can he present conclusive evidence that the country *can* deal competently with such problems? Some of these are associated with the problem of adequately resolving the questions and doubts of an enlightened public.

Mr. Eisenbud states categorically: "Only by a sustained, well-organized, well-directed program of education can we be assured that the public will some day be ready to accept the atomic-energy industry and its associated public health hazards in a rational manner." And: "The country needs a public-information program that will provide every segment of the community with the information it needs to live with radiation in the same rational manner in which it lives with other environmental risks."

I disagree with both the latter statements. The reason why the lay public and portions of the scientific and medical communities are presently concerned is that, having become educated and knowledgeable, they know what to be concerned about. They are aware that one agency, the AEC has been charged with the double responsibility of promoting nuclear energy and protecting the public. They doubt that one bureaucratic head can act properly and impartially in both categories.

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It is my opinion that the public does not demonstrate as much concern over other and greater environmental risks due to its trust in governmental agencies (e.g., water supplies, food and drugs, occupational safety, transportation and laws generally safeguarding public health).

The public-health hazards associated with the atomic-energy industry are complex and cannot be understood by lay persons or scientists without exhaustive study and research. Problems presented by these hazards and the decisions involved must be left to experts who enjoy public confidence. The best way to gain this trust is to consummate, as soon as possible, adequate programs in federal, state and local agencies charged specifically with protecting the public in this area.

Health and safety aspects of the atomic-energy program must be divorced from the AEC at both federal and state levels.

JAMES L. DALLAS
290 Essex Street
Beverly, Massachusetts

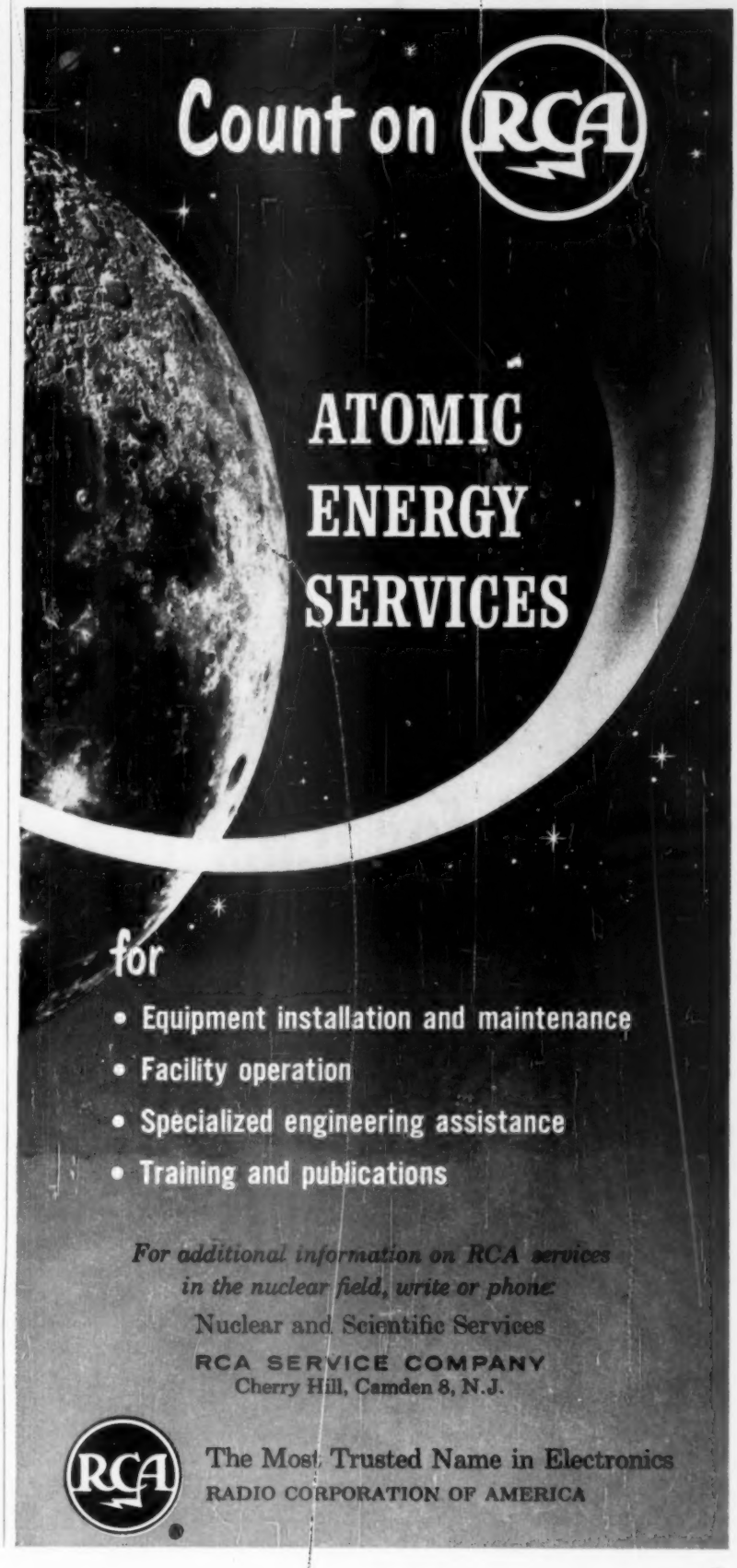
DEAR SIR:

Having reviewed the films listed by Mr. Clark, I'm afraid there must remain a difference of opinion between us as to whether these films are in fact helpful in explaining the radiation hazards of the civilian atomic-energy industry. Although the films may be satisfactory for certain types of employees and community-relations problems that arise in the vicinity of large AEC installations, they are, in my opinion, not suitable for the general public in many parts of the country where the potential hazards are from low-level wastes or the use of materials that are only mildly radioactive.

—MERRIL EISENBUD, Professor
Institute of Industrial Medicine
New York University Medical Center
New York, New York

Erratum

The following late-arriving information was not included in the NUCLEONICS Table of Neutron Sources (Dec. '60, p. 66). Entries follow the order of the columns in that table: RCL Model 70001; Radiation Counter Laboratories, Inc., (5121 W. Grove St., Skokie, Ill.); *d*; 0.075–0.2 Mev;—; 0.01 kw; 0.1 ma; 0.5 cm; 3 μsec; 10–100 pps; 3×10^{-4}; 3×10^{-4} ma; 0.1 ma; 5×10^{5} n/sec; 1.6×10^{12} n/sec; 10^{7} n/cm²/sec; 4×10^{3} n/cm²/sec; 10^{5} n/cm²/sec; 10^{8} n/cm²/sec; $12,500.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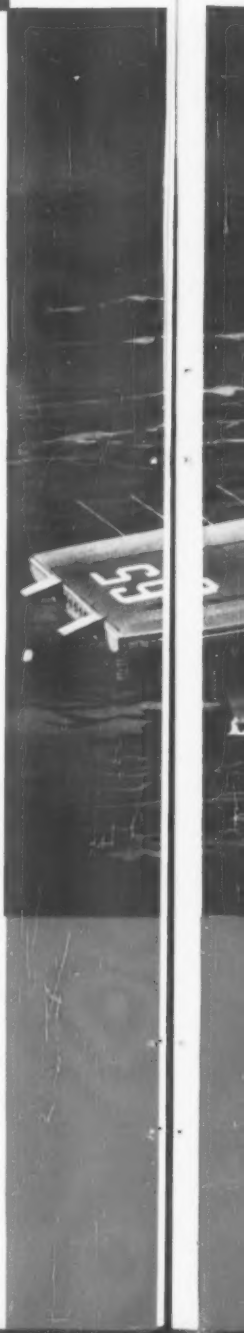

U.S. NAVY SERVICE APPLICATIONS INCLUDE: Pipe for valve operating system reservoirs and primary water preheaters.

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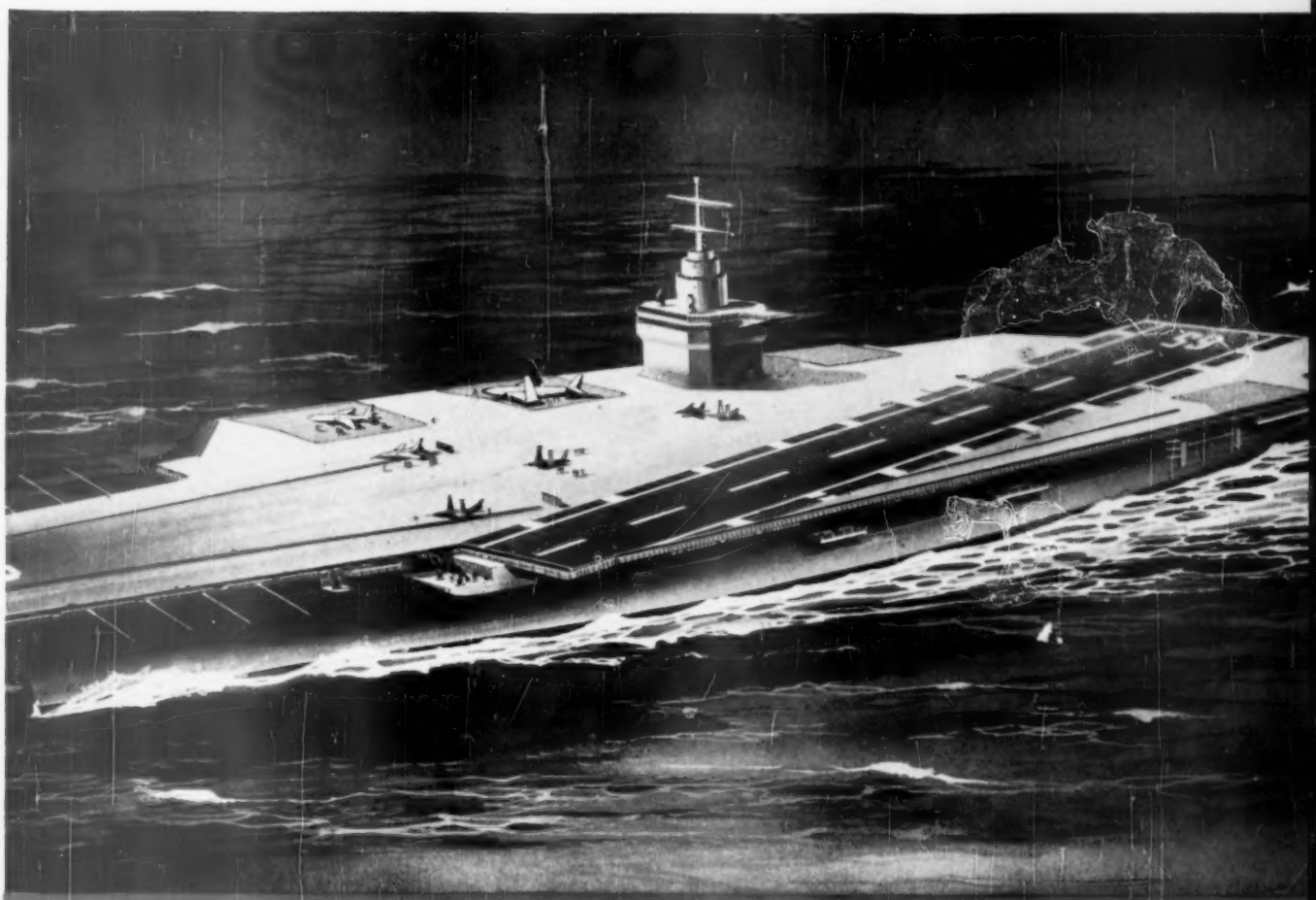
The U.S.S. Enterprise, our first nuclear-powered super aircraft carrier, can cruise at great speed and for almost unlimited time and distances without refueling. The Enterprise, built by Newport News Shipbuilding and Dry Dock Co., ushers in a new age of mobility and power for air and surface warfare at sea. At left, the Skipjack, nuclear-powered and with revolutionary blimp-shaped hull, is the fastest of the A-Subs. Both vessels utilize hydroforged fine-grain stainless pipe supplied by United States Pipe and Foundry Company.



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One of a series.

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In an isolated laboratory in southwestern Ohio, GM Research scientists have reduced the earth's magnetic field to one ten-thousandth of its usual strength. This is about as weak as the interplanetary field detected by the Pioneer V solar satellite.

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The beauty of the experiment is that the resulting values can be related directly to the motions of electrons in the rod. The values indicate the large portion of magnetization due to the *spin* of electrons . . . and the slight, but theoretically important, remaining portion due to *orbital* motion of electrons.

These measured values are helping scientists form a better understanding of the perplexing phenomenon — ferromagnetism. Currently being pursued in cooperation with the Charles F. Kettering Foundation, this long-standing project is one of the ventures in basic research of the General Motors Research Laboratories.

General Motors Research Laboratories

Warren, Michigan

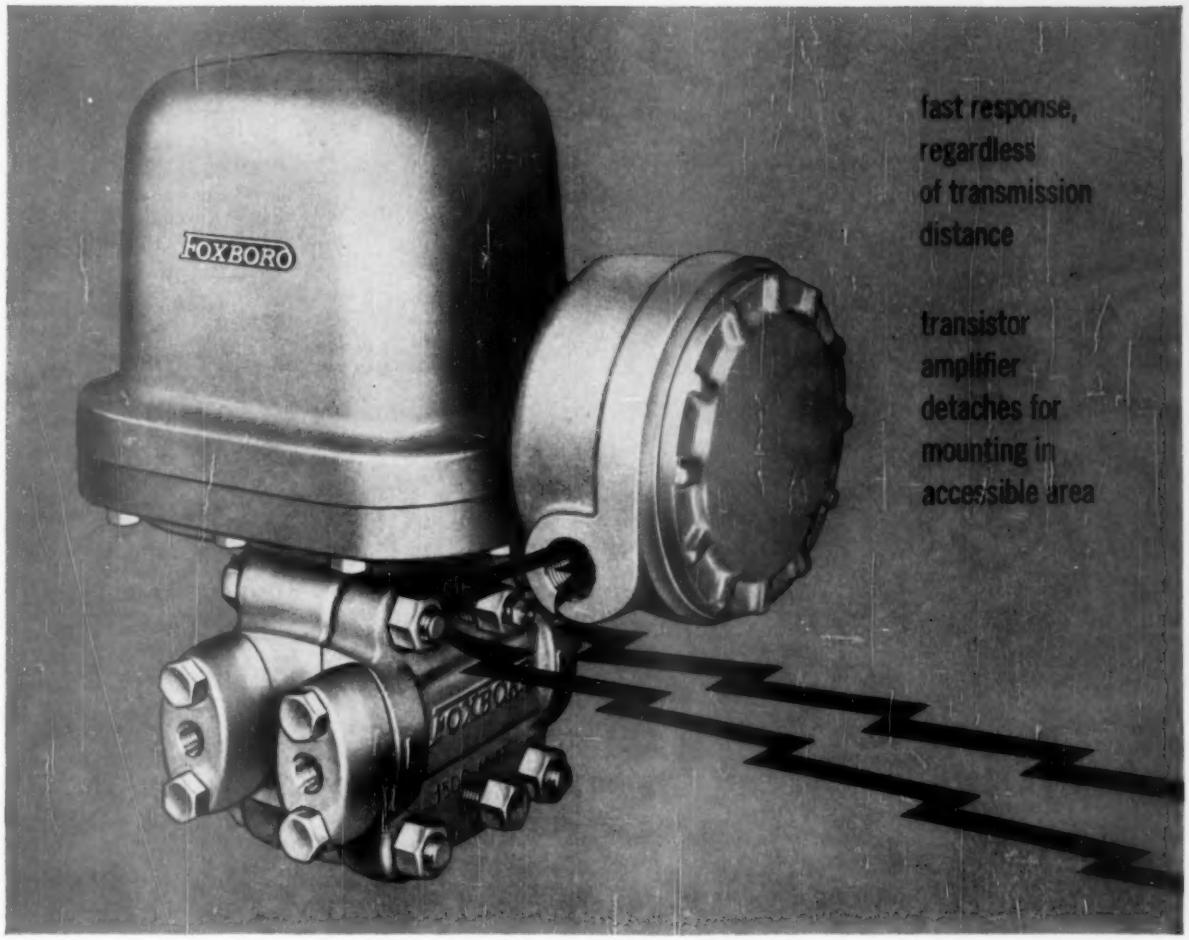
Gyromagnetic Ratios

	a	***b***
Iron	*1.92*	*1.90*
Cobalt	*1.85*	*1.83*
Nickel	*1.84*	*1.83*
Supermalloy	*1.91*	*1.91*

Comparison of (a) gyromagnetic ratios measured in the new Kettering Magnetics Laboratory with (b) corresponding ferromagnetic resonance measurements. These ratios would equal 2 if magnetization were due only to electron spin, or 1 if due only to orbital electron motion.

System of Helmholtz coils used to neutralize earth's magnetic field.

introducing the Foxboro electronic d/p cell* transmitter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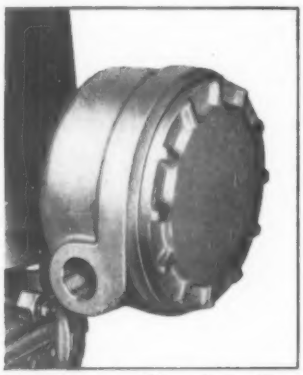
fast response, regardless of transmission distance
transistor amplifier detaches for mounting in accessible area



Transistor amplifier of the Foxboro Electronic d/p Cell can be detached for relocation in an accessible area, so that all transistors are removed from possible contamination. Separate mounting has absolutely no effect on accurate measurement and transmission.

Yes, Foxboro has taken its famous pneumatic d/p cell transmitter and added to it the benefits of electronic transmission. Look at the results:

- true force-balance design for lowest displacement — fastest response
- solid state throughout — no vacuum tubes to replace
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- same body, same performance as thousands of pneumatic d/p cells now in operation
- ranges from 5 to 850" of water — maximum working pressures to 6000 psi

And then, of course, you get the same positive overrange protection, the same high sustained accuracy, the same rugged construction that has always been standard with the Foxboro d/p cell transmitter.

Foxboro electronic d/p Cells are presently in use measuring and transmitting: pressurizer level, primary coolant flow, and steam generator 3-element feed-water level and flow. For full details on this important unit in the Foxboro Electronic Consotrol* family, get in touch with your Foxboro Field Engineer. Or write for Bulletin 21-10. The Foxboro Company, 621 Neponset Avenue, Foxboro, Mass.

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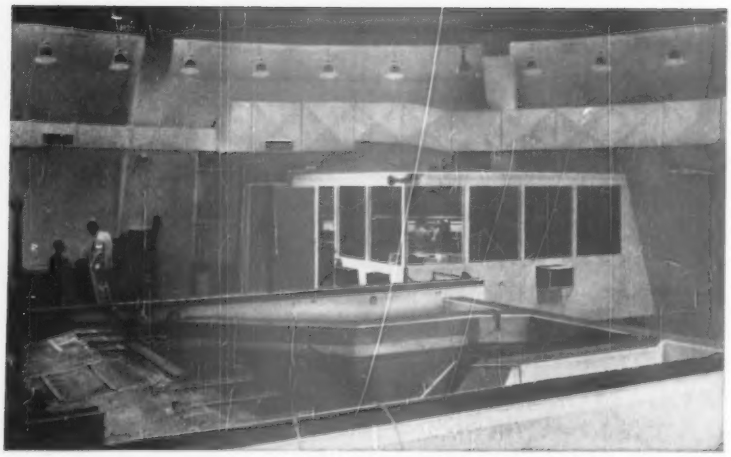
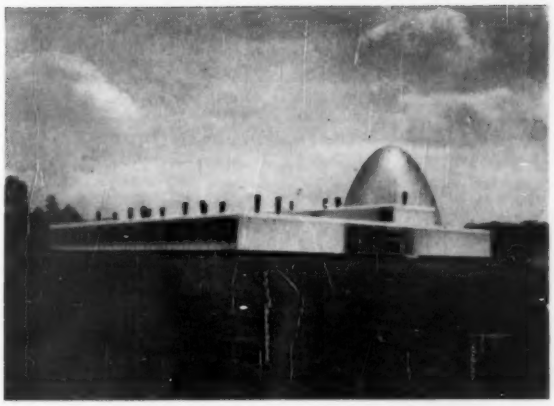
at the "Atoms for Living" Center . . .

10 companies share Honeywell



This view shows the top of the "swimming pool" and the reactor control room. A core of enriched uranium is located at the bottom of the pool, 30 feet below. 136,000 gallons of demineralized circulating water provide additional shielding and remove heat from the core when the reactor is operating.

Honeywell instruments for startup, linear, log N, and safety channels, along with auxiliary equipment, are mounted on the panel to provide good readability from the operator's position at the console. Rod drive, power set, range selector, rod position indicators, scram button, scram warnings, and secondary annunciator system are on the console within easy reach.



An 87-foot-high aluminum-sheathed concrete dome houses the reactor, and is designed to provide maximum safety from radiation hazards.

instrumentation for safe reactor control

Ten non-competing industrial companies were in need of facilities for nuclear research in their respective fields of interest, so they pooled their resources to form Industrial Reactor Laboratories, Inc.—an "Atoms for Living" center near Plainsboro, N.J. Now, each company has at its disposal the world's largest privately owned nuclear research reactor—at one-tenth the cost of single-company ownership. IRL owners are American Machine & Foundry Company, American Tobacco Company, Atlas Powder Company, Continental Can Company, Corning Glass Works, National Distillers and Chemical Corporation, National Lead Company, Radio Corporation of America, Socony Mobil Oil Company, Inc., and United States Rubber Company.

The reactor is a 5-million-watt "swimming pool" type, designed and built by American Machine & Foundry Company. Like many major nuclear installations in the country, Industrial Reactor Laboratories use Honeywell instrumentation for safe, accurate, dependable control. In your own project, use Honeywell's extensive experience in control of nuclear processes—experience that includes design and construction of reliable components, building complete reactor control systems, and actual installation and startup. Call your nearby Honeywell field engineer. He's as near as your phone.

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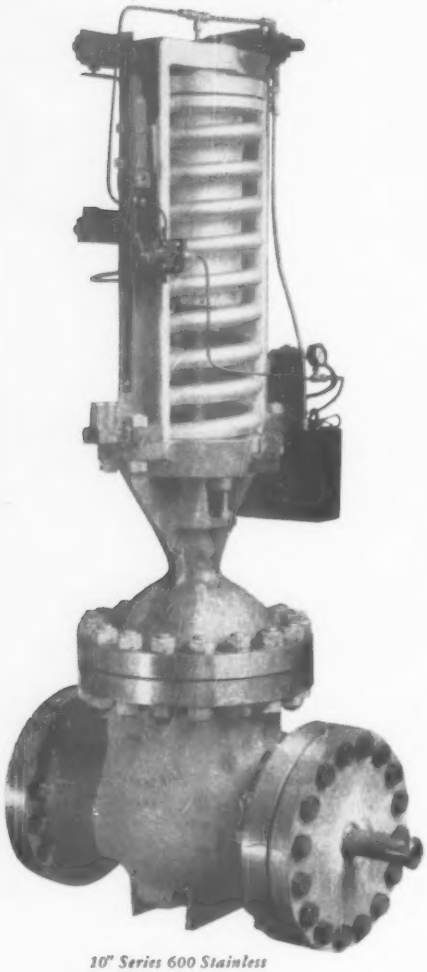

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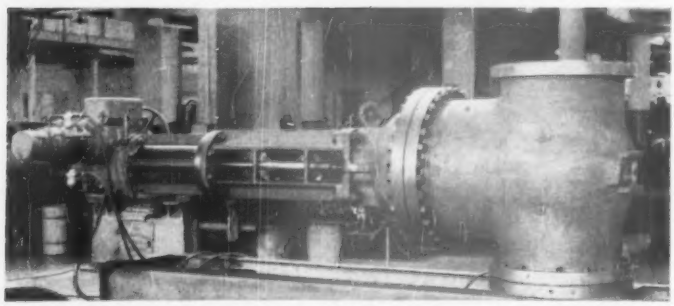

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TESTING AT SITE—here, in one of 12 General Electric operating instrumentation installations—helps assure complete system coordination.

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2. Safety systems
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COMPONENTS:

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2. High-voltage power supply
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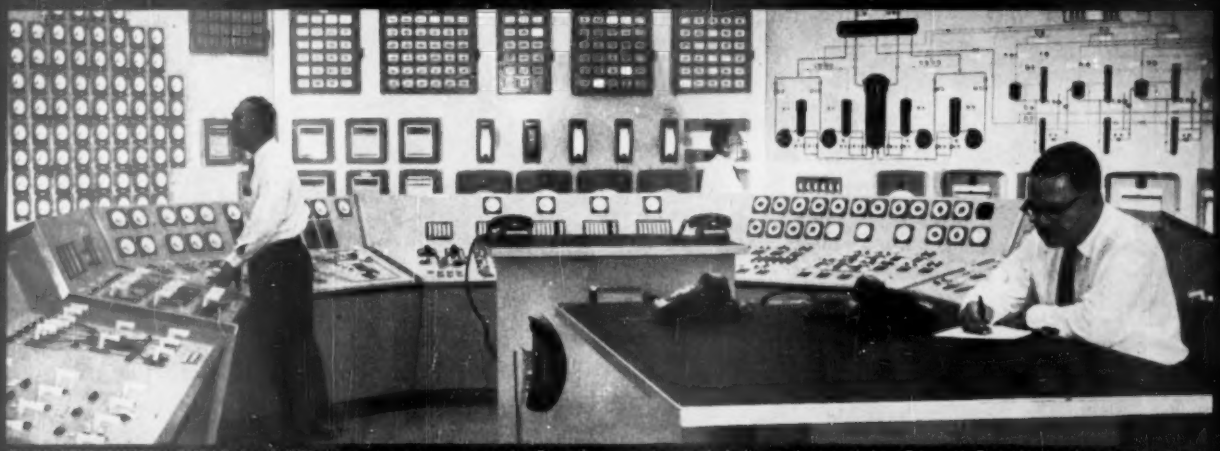
4. Log count rate meter
5. Log count rate meter with period
6. Linear count rate meter
7. Preamplifier
8. Flux amplifier
9. Actuator amplifier
10. Logic element



COMPLETE INSTRUMENTATION SYSTEMS, such as this one at the Dresden Nuclear Power Station, and individual instruments for wide application are engineered, built, and tested by General Electric at the Atomic Power Equipment Department in San Jose, California.

General Electric nuclear instrumentation has already been specified for 23 nuclear reactors

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Many instrumentation items are now "off-the-shelf" equipment. Also General Electric provides complete system responsibility, safety and control equipment design and manufacture. For more information on any G-E commercial nuclear activity, including complete reactor systems, contact your General Electric Apparatus Sales Office. Outside the United States and Canada, write to International General Electric Company, 150 East 42nd Street, New York 17, N. Y. 133-03

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Space, Administrative Problems Occupy Forum Meeting

Trying to capture and summarize the mood of the atomic industry at its annual get-together, held this year in San Francisco Dec. 14–16, one could fairly say that it had one eye cautiously, hopefully looking for modest improvements in the business picture, and one fascinatedly fixed on nuclear applications in outer space.

Two of the major after-dinner speakers at the Atomic Industrial Forum meeting emphasized the space program and what we should be doing to gear up for it. Congressman Chet Holifield (D-Calif.), who takes over this month as chairman of the Joint Committee on Atomic Energy, had some strong words of support for the Atoms-in-Space program—as well as some equally strong words calling for an end to governmental indecision with respect to it. Likewise Francis K. McCune of General Electric, chief industry spokesman at the meeting stressed the industry's responsibility in meeting the space challenge. (McCune spoke as retiring president of the Forum—he was succeeded by Charles H. Weaver of Westinghouse.)

The Forum devoted two of its ten sessions to considerations of nuclear problems in space, and the American Nuclear Society (meeting Dec. 12–13) had one entire session on this subject.

As for the business picture, the meeting seemed to continue the upswing of guarded optimism (noted a year ago, NU, Dec '59, 17). While the reactor industry is certainly still a hungry one, and while the "stalled reactors" in the AEC fiscal '60 program are mostly still stalled, meeting participants seemed to take heart from the three large-scale new projects initiated this year in 1960 or to be initiated in 1961 (Southern California Edison, Pacific Gas & Electric, and ESUPRA). Components and fuel manufacturers at the exhibit, Atom-fair-West, had nothing but praise for the show, which drew 6,000. ANS had an all-time record high registration of 1,127; the Forum meeting's 300 was certainly cut by the blizzard in the East early in the week that disrupted transportation.

HOLIFIELD SETS COURSE

In his keynote address at the AIF-ANS all-conference banquet, Holifield laid down some guidelines he may be expected to follow during his two-year stint as JCAE Chairman:

On Speed: "Time is an important element in any policy. If we drift . . . leadership in important areas in nuclear technology will be lost to the U. S. AEC and industry have had warning on our problems of leadership and urgency . . . In any competition the advantage rests with the swift. Our policy, then, with respect to advanced applications, should dictate leadership and urgency but not recklessness—calculated speed but not waste. Above all, decisions must be faced and not delayed."

This note of urgency ran through all of Holifield's speech:

On Programs: "It still takes AEC too long to develop and recommend projects, and still longer to get construction started after authorization. The AEC finally began to recognize this problem of long lead time more than a year ago. But I regret to say that progress is still too slow."

On Advanced Reactors: "The water reactors have benefited from close to a billion dollars' worth of federal research and development. . . . The other reactor types have had far less support. Private financial support can be found for the water reactors but private companies are less willing to risk money on the more unknown types. Whether or not additional federal financial assistance in these established reactor technologies will be needed is something we will have to face during the next years. But we can be sure that additional federal assistance will be required for other than the water type reactors, if these types are not to die on the vine. . . . I am willing to be open minded [as to how these reactors shall be financed]. I only ask that the decisions be faced—not neglected. If new starts are in order, I only ask for sensible finance plans."

On Rocket Propulsion: "As to whether or not this [world's first demonstration of nuclear rocket capability] should be a ground-launched nuclear rocket, or an upper stage of a Saturn or other conventional rocket, I am willing to leave to the advice of the experts. All I want is that the decision be based on nuclear rocket technology, and not be based on rigid extrapolations from conventional rocketry or from solely budgetary considerations. But the greatest danger in the *nuclear* rocket program is delay. A 1965 flight date can be met, but it can also be postponed. . . . Let's set a flight date and convert the then-existing technology

McCone says he wants to quit AEC on Jan. 20

Washington was rumor rampaging last month on the successor to AEC Chairman John A. McCone, who said he wanted to leave his post on the last day of the Eisenhower Administration—Jan. 20. Robert A. McKinney, a man of varied experience in the program but not a great deal of support within the nuclear field, was being sponsored for the job by Sen. Clinton P. Anderson (D-N. M.), chairman of the Joint Committee on Atomic Energy until he turns the job over to Rep. Chet Holifield (D-Cal.) this month.

Givet project may be delayed by financing

The Belgian partners in the Franco-Belgian reactor project in the Ardennes, near Givet, France, (NU, Aug '60, 22), have asked for a five-month postponement of final contract signing until they can work out some financing problems. Deadline had been Jan. 1 but the Belgians have suggested a delay until May 31. Subject to negotiation of financing and other problems, the 210-Mwe pressurized-water reactor is to be ordered from the group Westinghouse-Framatome-ACEC.

into a mission capability. Let's not mix the ideas of improvement and flight demonstration. Logically, improvements comes later."

SNAP AND RAMJET

On SNAP: "As things stand now, the most powerful space reactor programmed in the SNAP [Systems for Nuclear Auxiliary Power] effort would produce some 30–60 kw. Electrical propulsion experiments using this 30–60-kw plant are being programmed in 1965 to 1966, but, admittedly this is a very low power experiment. It is hardly meaningful. There seems to be rather universal agreement that before the 1970's nuclear power units in the range 1–10 Mwe will be needed for the big lunar and interplanetary missions. These nuclear space power units take a long time to develop and must be initiated far enough in advance of required flight dates to insure adequate performance and reliability when needed."

On Pluto: "I would hope that this missile [nuclear ramjet] gets a fair test and is objectively evaluated. . . It would seem almost impossible to identify someone in the Dept. of Defense who can take a clear-cut decision on whether to go forward or not. This decision must be made and there should be definition of the urgency which surrounds the development of this capability. . . . Why not end the delay and program an early flight demonstration?"

On Remote Reactors: "Use of nuclear plants at remote locations like Antarctica or Greenland could save considerable money by providing more economic electric power. . . . We have gathered informally that neither the Navy, AEC, or the Budget Bureau has included any Antarctic reactors, or other reactors for remote sites in their 1962 budget requests. This problem of the remote site reactors must be faced and it will be! And I can assure you that the Joint Committee will stay on this until it is satisfactorily solved."

ARE REQUIREMENTS REQUIRED?

One of the more intriguing passages in Holifield's talk was a reference to the increasingly vexing problem caused by application in nuclear programs of the Defense department's rule that a specific mission requirement must be shown for a device before a development project on it may be undertaken. It was in connection with his discussion of the SNAP program that Holifield commented, "I am aware of nothing in the Atomic Energy Act which says that the AEC needs formal requirements from another agency to conduct nuclear research and development, but I may be missing something. It would seem to me that the Commission should proceed independent of a requirement from another agency if the research and development appears necessary and desirable."

Regarding recent industry complaints of unfair competition by AEC at its facilities, Holifield said, "Of recent years some have pitted the laboratories against industry in a fictitious competition. The national laboratories of the AEC are not competitors of industry. Their primary role is to do advanced research and development. Industry automatically benefits from their pioneering efforts. If the laboratories were weakened, fewer programs would be ready for industrial participation."

In a press conference prior to his address, Holifield said he would like to see spending on nuclear power increased from $200- to $400-million annually. And he took a definitely conservative stand on the question of reactor siting. When asked about this problem—an increasingly formidable one for industry—Holifield replied that there are conventional electric generating sites at Boulder Dam, Shasta, and other places not close to population centers. "Granted that long transmission lines are not as economic," he went on. "But I don't see why there's all the excitement about putting reactors near populated places. There needn't be any problem. As long as the engineering safety is not worked out, we have got to let that control siting of reactors—not economics. Safety can be engineered in. But this isn't done overnight and it will take a little time until wise men can say that putting reactors next to populated places no longer constitutes a danger."

IF INDUSTRY IS TO LEAD

GE's McCune pointed out some of the tasks industry must attack if it wants to see a "transition of the atomic energy business from a government monopoly to a reasonable private enterprise." First among these he named development of new business methods: "The technical aspects of this business have been the main focal point of the industrial effort to date. Unfortunately we have not given equal attention to some of the business problems. If we have learned anything from a business standpoint, however, it is that traditional concepts and practices may not always be sufficient to do the job. The unprecedented social and political dimensions of this new energy source demand a flexibility of mind and management not common to the business world of the past."

Public fear of atomic energy, government control for security and international prestige reasons, and constantly fluctuating threats of nuclear

ANP REACTORS: HTRE Units Declassified

AEC declassified last month the High Temperature Reactor Experiment program including the three experiments, HTRE-1, -2 and -3 at the Aircraft Nuclear Propulsion area of the National Reactor Testing Station in Idaho. Design and performance details, revealed at the American Nuclear Society's winter meeting, have led to the hope the first direct-cycle nuclear-propelled plane will be in the air by 1965. Calculated dose-rate to the plane's crew using such a reactor would permit them 1000 hr/year of flight—a normal operating range—or half a million miles without landing.

HTRE-3 has run 120 hr at a power level of 35 Mw(th) feeding hot air to two J-47 jet engines. (See article on p. 45 for full technical details.) Fuel elements for the reactor (*see photo*) operated at 1850–1900° F and were made up of concentric annuli of fully-enriched uranium clad in nicrome—80% nickel, 20% chrome. Now, advanced all-ceramic fuel elements—not declassified as yet—are being tested. They will fuel the final ground test reactor prototype, an advance on HTRE-3 designated P-140, now being designed.

NOW-OBSOLETE FUEL ELEMENT, clad in nickel-chrome alloy, was used in HTRE-1 —later versions in HTRE-2 and -3 (note pencil)

war have complicated industry's assumption of leadership, McCune said, but "there has been a tendency on the part of the industry to use these complexities as an excuse for inactivity, an indulgence that cannot be tolerated if we expect our competitive system to survive."

"The situation calls for renewed activity on the part of the industry," McCune said, "to compete for AEC research-development funds, cooperative programs, and in those areas such as Euratom and NASA where there are fewer long-term commitments to support government laboratories and reactor facilities. More emphasis should be placed on long-range planning in order to work out programs with the policy-making people of the AEC well in advance of the time the work is to be performed. Submitting unsolicited short-range proposals with the expectation of early acceptance will be a fruitless exercise unless the basic programs and the necessary funds have been approved long in advance."

Another industry problem spotlighted by McCune is simplification of AEC licensing procedures. "The difficulties of this task," he observed, "have been compounded by the tendency of some segments of our own industry to seek informal AEC approval on increasingly minute design details in an effort to avoid expenditures on the development of hardware which will subsequently come under AEC review. Such activity cannot help but increase the layers of formal government review and the irony of it all is that these additional restrictive procedures will have been initiated not by the government but by the industry which is being licensed."

SPACE SAFETY

Two subjects dominated the papers read at the Forum sessions: space, and administrative problems of AEC-Industry relationships.

In one of the first official glimpses-behind-the-curtain on a relatively new vital problem, Lt. Col. Joseph A. Connor Jr., USAF, chairman of AEC's Aerospace Nuclear Safety Board, discussed the safety aspects of the nuclear space program.

His conclusion: "Appraisal of the radiation risks [for nuclear rockets and SNAP devices] reveals them to be no more than those risks encountered in the progressive development of steam and electric power, the airplane, the automobile, the rocket, or even something as basic as fire."

Worst assumed accident for a SNAP reactor—strong inversion weather condition, one hour of full operation, a 50 Mw/sec excursion and release of all fission products—would result in only 60 millirem exposure directly downwind at the center of the fission product drift at 12 miles. For a Kiwi-type rocket reactor, under similar worst-conceivable conditions, fission products directly downwind in a narrow belt could give a dose of 400 millirem at a five-mile radius and 200 millirem at ten miles, during the first 13-week interval. Though this is greater than the recommended 170 millirem/yr for members of the population at large, the dosage would be only 100 millirem if one stood in the open for one hour in the center of the fission product drift instead of remaining 13 weeks, and, of course, any move out of the center of drift would result in much less exposure.

"Use of the vast Nevada test site for ground testing essentially eliminates this problem, "Connor said, "and present information does not warrant restriction of project development." It is anticipated that a Rover rocket could be flight tested in the Saturn system from Cape Canaveral; SNAP isotope and reactor devices can probably be flown safely with existing technology on either a polar orbit trajectory at the Pacific Missile Range, or a southeast trajectory at the Atlantic Missile Range.

ADMINISTRATIVE PROCEDURES

Treatment of administrative problems fell basically into two categories: how to get along under present conditions with existing difficulties on reactor siting, on licensing, on contracting practices and in the international market; and whether or not AEC ought to be split into separate agencies for its promotional activities on one hand and its regulatory and licensing ones on the other.

On the second question, a resounding "yes" came from William Berman and Lee Hydeman of the Univ. of Michigan, and an implied "yes" from Fritz F. Heimann of General Electric. However, at his press conference, Congressman Holifield indicated that it was unlikely any separation would come in the next two years:

"I question if the Commission should enter a broad field of regulation in peacetime efforts. As we get more reactors, we will need more regulation, more inspection, more watchfulness. That's why we passed an enabling law permitting the states to take over when they are qualified. They are training people, but haven't yet the trained manpower to do it.

"I would like to see AEC get back to the job it was set up to do: to push development. But until the states qualify themselves to do regulation, we have to continue that on a federal level, and that's why I'm not pushing this. Until we get trained people, we have to continue as we are and work at this thing gradually."

In another major address, Robert McKinney, author of the recent five-volume study of the U. S. foreign atomic activities, made a plea for better coordination of the research and development efforts of Western countries. He said: "Atomic research and development programs in North America and Western Europe can be planned on a cooperative basis, while still insuring full national autonomy in decision making. . . ."

Radiation at the Forum

Some additional radiation applications were discussed at a Forum session by spokesmen for companies engaged in this field. John W. Olander, Manager, Industrial Radiation of High Voltage Engineering Corp., mentioned that there is increasing interest in the effect of radiation on the properties of some semiconductors. Vacancies in crystal lattices of semiconductors are thought to contribute to their operation: bombardment by a given number of electrons is a controllable method, said Olander, for creating defects in the crystal structure with a high degree of uniformity. Characteristics such as switching time and storage time after manufacture can be improved. And the process lends itself well to continuous production, he said.

J. G. Morse, Manager, Isotopic Power Dept., Martin Co., discussed his company's development of a design for a series of remote weather stations, powered by isotopic nuclear power (patterned after the SNAP-3 concept) which would automatically transmit their weather information. Typical station would operate for two years without attendance or maintenance. Power would be provided by a generator with a 100-thermal watt strontium-90 heat source. Generator produces five electrical watts and continuously charges a nickel-cadmium battery with rated capacity of about 7 times the discharge requirements. Stations would transmit weather data every three hours with extra power going to heat the station itself. He estimated the production cost of 5-watt generators using Sr-90 titanate as fuel at about $10,000 each, including cost of fuel, generator, and shield. This would mean a cost of $0.03 per watt/hr (not counting credit for reselling spent fuel)—compared to battery cost of $0.20 per watt/hr for 10-year capability.

1960 Ends with Flurry of Major Reactor Developments

1. So. Cal. Edison, Westinghouse agree
2. ESUPRA group signs with GE and GA
3. ConEd re-examines second Indian Point reactor
4. SENN considering second reactor, too

The first year of the 1960's—the decade which is virtually certain to bring competitive nuclear power to the U. S.—was closed out last month with a flurry of significant developments on this score:

1. Southern California Edison and Westinghouse reached general agreement on the utility's purchase of a 360-Mwe pressurized-water reactor (NU, June '60, 1), then filed proposals with AEC for assistance on research and development (to Westinghouse) and waiver of fuel use charges (Edison). The price to Edison is $78-million, exclusive of land. Proposed site, for which negotiations were still going on last month, is the Marine Corp's Camp Pendleton, on the Pacific Coast midway between Los Angeles and San Diego.

2. ESUPRA a group of seven N. Y. State utilities announced cooperative agreements with General Atomic and General Electric to begin three-year development programs on, respectively, the high-temperature, gas-cooled concept and the light-water, nuclear-superheat concept—looking toward ultimate construction of a reactor in the 300–500-Mwe range by 1967–68 (NU, Dec. '60, 27).

3. Consolidated Edison of New York, nearing completion of its 275-Mwe reactor-fossil-fueled combination plant on the Hudson River, announced it was "checking once again on what a second reactor at Indian Point might cost, as compared to a conventional plant." Reactor industry sources said Con Ed was talking with General Electric and Westinghouse about a reactor which Con Ed said might be "of the order of 400 Mwe."

4. Italian sources disclosed that SENN (Societa Elettronucleare Nazionale) was seriously considering construction of a second reactor at the Garigliano River site of the 150-Mwe, GE boiling-water reactor now building; construction of the second plant would begin in 1962. The first plant is being built to permit upsizing to 225 Mwe if desirable after burnup of the first core (NU, March '60, 27).

Southern Cal Edison

The filing of third-round-type proposals with AEC by Edison and Westinghouse signalled the end of negotiation by these two firms on most major contractual considerations, although Edison was still negotiating with the Marine Corps on use of the Pendleton site. Aside from the site question, the crux of negotiations has shifted to Washington, where AEC and Westinghouse were discussing the amount of research-development aid AEC might provide; and AEC, Westinghouse and Edison were discussing waiver by AEC of the fuel-use charge. The results of these negotiations, in turn, must be reviewed by the Joint Committee on Atomic Energy.

Edison officials said they were proceeding on the assumption that the reactor would be competitive "over its lifetime," exclusive of AEC research-development aid to Westinghouse (estimated at something more than Westinghouse's $4.4-million estimate when the closed-cycle plant was announced in late 1959—NU, Oct. '60, 17). The two companies hope to get everything settled early this year—aiming for a start on the plant this year and completion by Jan. 1, 1965.

New York Project

The seven-utility ESUPRA group (Empire State Utilities Power Resources Associates) announced on Dec. 6 that they would not make an immediate start on construction of a reactor—rather, that they have agreed to support gas and superheat development programs to be carried out by GA and GE at a total expected cost of more than $20-million. Their decision to defer actual construction appeared to have two major bases: 1. no pressing need for a big plant on their combined grids until late in the 1960's; and 2. no desire to build such a plant until there is complete assurance that it will be economic (7 mills currently) and will produce high-temperature steam.

Forming a new non-profit corporation to sponsor the development work—ESADA (Empire State Atomic Development Associates), the utilities said they had made no commitment to build a reactor at the conclusion of either effort. And they emphasized a further point: They will look at other concepts equally as hard as gas and superheat when the time comes—in about 1963—to decide on construction of a plant. Breakdown of utility contributions to ESADA: Niagara Mohawk, 31%; Long Island Lighting, 17%; N. Y. State Electric & Gas, 16%; Con Ed, 16%; Rochester Gas & Electric, 9%; Central Hudson Gas & Electric, 6%; and Orange & Rockland Utilities, 5%.

GE Superheat Program

ESADA arrived at their total-program estimate of $20-million-plus this way: GE-superheat, $8-million for a 5-Mwe superheat test reactor to which ESADA will contribute $5.75 million and GE $2.25-million; GA-gas, $8.7-million in development work, with ESADA contributing $4.5-million, GA $4.2-million; and several million dollars more which GE will spend for superheat development. GE said it would ask AEC to shoulder some portion of this expense under the civilian reactor demonstration program.

The superheat test reactor will be located at GE's Vallecitos, Calif.,

N. Y. Power Body Restates Desire to Build Reactors

The decision of seven private utilities in New York State to proceed with a reactor-development program (story this page) was not uncolored by State politics—although, of course, competitive nuclear power was the main consideration. The possible entry of New York State Power Authority into the nuclear power field is considered a threat to the private utility industry and this was never clearer than in late November when the Authority's nuclear consultant, T. F. Farrell, released a new "position paper" on nuclear power. In a letter to Oliver Townsend, director of the State's Office of Atomic Energy, Farrell made these points: 1. that the public interest required both private and government construction of nuclear plants; 2. that the Authority was not seeking the "exclusive right" to build such plants; and 3. that the Authority was entitled to the same federal subsidies as those available to private companies.

"To bring the cost of atomic power down so that it will be competitive with power from other sources," Farrell said on behalf of the Authority, "will require building and operating of large plants. Both private enterprise and the Authority should devote their efforts towards this goal." The Authority must get legislative approval to enter the nuclear field; it would also require federal or other assistance "in order to build such a plant," Farrell said.

laboratory—close enough to the Vallecitos Boiling Water Reactor (VBWR) and a 150,000-lb fossil-fueled boiler to take steam from either or both of these sources. Essentially, the reactor will be a "pot of water" with fuel elements designed to superheat saturated steam of 1,000 psi (550 deg F) to 850–950 deg F at 925 psi. GE hopes to complete the reactor by July 1, 1962.

GA's Gas Program

As will the GE program, the General Atomic high-temperature gas program will aim at developing an economic reactor in the range 300–500 Mwe, with GA shooting to produce steam of 1,000 deg F and 2400 psi. GA and Bechtel Corp. are building the prototype of such a plant at Peach Bottom, Pa., for Philadelphia Electric and a group of more than fifty other utilities (NU, Dec. '58, 17).

GA said the major research problems to be tackled as the development program proceeds are: determination of exact admixture of fuel and moderator to be used; temperatures of the exit gases; and exact configuration of the fuel and method of absorbing fission gases. No longer a major problem, GA said, was fuel-element cladding. The development of impervious graphite cladding has advanced to the point that it will be used in the initial Peach Bottom core, rather than delayed to subsequent cores as GA originally feared might be necessary; only further radiation-effects data is required, GA said, to demonstrate the feasibility of graphite.

Significance of Decision

An important meaning of ESADA's selection of high-temperature gas and superheat is this: the overall view of those participating in the selection (pressurized water, spectrum shift and sodium-graphite were also considered) is that gas and superheat hold the best promise at this point of producing modern steam at competitive costs later in this decade.

The gas-superheat victory also had this significance: It virtually guarantees—subject to a complete collapse of the gas approach—the arrival of General Atomic as a future supplier of power equipment to the utility industry. If so, GA has used nuclear energy to qualify as the first new supplier to this industry in many years.

Nuclear Rocket: Planners Shoot for the Moon

Under the title, "Space—A New Mission for Nuclear Energy," Harold B. Finger, manager of the nuclear-rocket program for AEC and the National Space and Aeronautics Administration (NU, Oct. '60, 30), gave a New York scientific audience in late November an unprecedently thorough report on atoms in space. Highlights of Finger's speech to the local sections of the American Nuclear Society, American Rocket Society and American Astronautical Society:

1. Finger disclosed that his Office's initial goal is to develop a nuclear rocket soon enough to give the U. S. the distinction of putting the first human being on the moon. "I am pleased to note," Finger said, "that there is a growing conviction in the rocket business and in the space program that the vehicle . . . that will place our man on the moon will use stages powered by nuclear reactor rocket engines [a combination of chemical and nuclear rockets]."

First Kiwi-A Details

2. Revealed for the first time were a few details of the Kiwi-A reactor, first of the three test reactors operated at Jackass Flats, Nev., since the summer of 1959. "The Kiwi-A," Finger disclosed, "was a graphite reactor using flat plate fuel elements . . . approximately ¼-in. thick, with a .050-in.-wide flow passage separating the fueled plates." He also confirmed that Kiwi-A prime (operated this past summer) was considerably more advanced than Kiwi-A and that Kiwi-A3, the last in the series thus far, was a modified version of prime. Late this year, a series of reactors using liquid hydrogen as coolant is to begin.

3. Finger described the role expected to be taken by the engine contractor to be brought into the program soon (NU, Dec. '60, 31). The contractor, he said, would "provide necessary engineering support to the program and to undertake responsibility for research and development of a nuclear rocket engine. . . . The contractor selected will conduct all necessary engine-design work, engine-component and -subsystem applied-research work, engine-development testing, and—in the early phases of the contract—necessary support to Los Alamos."

4. Discussing rocket missions generally, Finger said he expected the Saturn vehicle, with nuclear stages, to handle many unmanned missions to the near planets Mars and Venus—becoming the workhorse for travel between these planets and earth. Electrical-propulsion systems, he said, will probably be used for longer-range missions, and a program of basic research on reactor systems to provide support for such electrical systems is well underway. Since these reactors will operate with liquid-metal coolant systems at 2,000 deg F—a temperature range for which good fundamental data is scarce—the government has scheduled some basic studies.

5. Disclosing some details of this basic research, Finger said NASA was supporting work on potassium and sodium (temperatures up to 2500 deg F) at Battelle Memorial Institute and the Naval Research Laboratory; that NASA had the Rocketdyne div. of North American Aviation working on the corrosion characteristics of metal vapors in containment materials; that NASA's Lewis Research Center and Oak Ridge National Laboratory were doing fundamental corrosion work; that Pratt & Whitney was studying the emissivity of waste-heat rejection radiator materials in hard vacuum; and that negotiations were being conducted with General Electric to determine the heat-transfer characteristics of boiling and condensing metals.

Rocket to Mars?

"The program we have laid out," Finger declared, "is aimed at providing answers to the [technical] questions [on chemical-nuclear systems] at a vigorous pace in order to be sure that the technology is available for application in our manned lunar landing vehicle when the decisions are made in defining the configuration of that vehicle. Before that decision is made, our program will have established, through ground testing, the feasibility of nuclear-rocket propulsion.

"During the course of early development of the manned lunar landing vehicle, our program will require flight testing of nuclear rocket stages to provide design and performance data to the launch vehicle development program. In addition, we will continue and expand our efforts at evaluating new reactor concepts and new materials for these reactors to provide maximum temperature, and, therefore, maximum specific impulse in the lightest weight systems possible. . . .

"We must have assurance of continued material resources to permit execution of a sound and vigorous program. . . . I believe strongly that the application of nuclear energy in the space-propulsion program is essential if we are to have freedom to travel at will in space. . . . "

HVEC-Arco Challenge: Crack Industrial Radiation Market

The world's most powerful and versatile organization for the manufacture of radiation machines has emerged from the consolidation six months ago of High Voltage Engineering Corp., Burlington, Mass., and Applied Radiation Corp., Walnut Creek, Calif. (NU, June '60, 28). In its essence, the merger (or consolidation, as both prefer to call it because each retains its identity) has put each firm in position to make a renewed onslaught on an elusive market—the use of electrons for industrial processing. The determination to "crack" this market was an underlying reason for their merger as it was in the original formation of each—HVEC in 1946, Arco in 1953.

For Arco, the consolidation offers an acceleration to early, widespread utilization of its microwave linear accelerator (linac) via the financial, marketing and research capabilities of HVEC. For HVEC, which was particularly attracted by Arco's linac, it adds a capability in machines of higher energy than HVEC's classic Van de Graaff accelerators and a research team complementary to its own, plus a facility on the West Coast. For both, the merger brings an unprecedented opportunity to add to their 250 customers using machines in research a much longer list, it is hoped, of customers using the machines for production.

In short, the "marriage" is one in which the bride and groom offer almost perfectly complementary dowers: Arco with unique high-energy microwave capabilities, HVEC with electro-static and low-energy electromagnetic capabilities; Arco located on the West Coast, HVEC on the East; Arco with a particularly strong microwave research group, HVEC not quite as strong in that area; and Arco with virtually no marketing organization, HVEC with both domestic and international marketing capabilities.

New HVEC Facility

High Voltage Engineering Corp. has installed a 2-Mev, positive-ion accelerator—the centerpiece for a combination service center and laboratory using positive ions and neutrons. Installation of the facility reflects the growing interest in these particles for activation analysis (thermal or fast neutrons), surface activation analysis (protons and deuterons), radiography (neutrons), autoradiography (positive ions, neutrons) and short-lived radioactivation (neutrons) in process control, where radiation is introduced briefly into fluid and solid systems for observation of flow rates and directions.

Decision to Merge

In a joint interview with Arco President M. Richard Jeppson and HVEC President Denis Robinson, Jeppson described the merger preliminaries this way: "Arco was looking around for a partner. . . . In building up our business, it was a choice of finding a partner—or going to the public—for investment capital. . . . Also, because of growing European markets and competition, Arco was very much interested in working out a European association [HVEC had already established a subsidiary in Amersfoort, The Netherlands].

Robinson explained HVEC's reasons: "We were making some retained earnings and had some [extra] capital. . . . We had been considering an irradiation facility on the West Coast. We [and Arco] complemented each other scientifically—we were the same breed of cats. Jeppson and his men had grown out of Berkeley [University of California] and we and our men had grown out of Massachusetts Institute of Technology.

"We had found it increasingly difficult to get the brains for the many challenges we faced. We couldn't get technical talent fast enough. Many California organizations were pulling people away from this [East] Coast—we were always bucking that situation.

"Arco's microwave linear accelerator complements perfectly what we have here [primarily the belt-driven Van de Graaffs and HVEC's new-electro-magnetic machines (NU, Aug. '60, 54)]. The belt machine does not easily go above 4-Mev electrons; nor do the magnetic machines look economic, for various reasons, above 4 Mev. It is easy to see that the energy capability of the microwave system is required for greater electron penetration, and of great interest for high-energy research programs."

Increasing Competition

Robinson said HVEC was also feeling "increasing pressure" from "the big companies," naming Hughes Aircraft, General Electric, Varian Associates (*p. 28*) and several in Europe.

"We definitely here at HVEC," Robinson continued, "felt the need in our Marketing div. for a strong and useful accelerator program in the high-energy range of electrons. HVEC had gotten into the linac field in 1950, delivering its first machine in 1953 or 1954. We went on but did not try to bring in new capital to develop the linac exclusively. Arco, however, did—going all out on this microwave machine. HVEC's pace was not fast enough. . . .

"[Also,] HVEC already had the beginnings of an international sales force—and Arco was trying to establish an international [and domestic] sales organization. We thought that if we could offer the whole gamut of accelerators through one set of men we had a much better chance [of competing]."

Jeppson touched on another basic reason for the merger in pointing out that the linac was not yet a profitable machine ("Nobody has made a penny—or even broken even—on the linac, here or abroad."). But both com-

NEW MANAGEMENT TEAM in radiation-machine field: President Denis Robinson of High Voltage Engineering Corp. (left) and M. Richard Jeppson, president of Applied Radiation Corp., which is now a High Voltage subsidiary

panies feel, he added, that the development investment in the microwave technology will pay off in "something like five years," or by '62–'63. Robinson compares this time-span with that of the Van de Graaff, which was invented in 1928, went into development in 1931, and was first sold commercially in 1946.

Industrial Processing

The concern of men like Robinson and Jeppson with industry's reluctance to make greater use of radiation is striking and, at first blush, anomalous —since both firms have seen their growth come from the scientific use of radiation machines (currently, 75–80% of HVEC's sales and all of Arco's sales are of this type). The research business has been lucrative and is regarded as one that is far from saturated, but these men leave little doubt that their greatest challenge is to develop radiation equipment reliable and economic enough to rate radiation with conventional energy as a basic tool for industrial production. From the first, both have expected more from the industrial market than has actually developed; recently, however, has come a series of small but promising programs to signal a possible upsurge. As Lincoln said about the Presidency, "the taste is in the mouth," and the "taste" of industrial radiation at Burlington and Walnut Creek gets a little stronger as the large-scale use of radiation machines gets a little closer.

"At the moment," Robinson observed, "the future is clearly marked [for radiation machines] in the research field. It is much more fuzzy in the commercial field."

Jeppson added: "For the first time, there are some clear indications in the industrial field [referring to relatively small-scale use of radiation for sterilization and for producing plastic film, hook-up wire, etc.]. There is a great deal more interest in the industrial field . . . but to forecast exactly what the industrial people intend to do with the machines is difficult."

Merger Details

Early this year, HVEC will present to its stockholders the first consolidated financial report reflecting the Arco acquisition; Arco stockholders had been given one share of HVEC stock for 10¾ shares of Arco, thus retiring the Arco stock and making the company a subsidiary of High Voltage. The consolidated statement will also include HVEC's Netherlands subsidiary, High Voltage Engineering (Europa), and Electronized Chemicals Corp., another subsidiary which operates HVEC's irradiation service vault at Burlington and holds certain patents. HVEC has two other subsidiaries: Goodrich-High Voltage Astronautics, Inc., owned jointly with B. F. Goodrich Co.; and Glass Grinding Corp., another jointly-owned subsidiary at Whitman, Mass., which grinds glass and ceramic components.

A major provision of the HVEC–Arco merger was consolidation of the two marketing forces into one, with headquarters at Burlington under E. Alfred Burrill, vice-president. Also, HVEC's Jack Nygard has reported to Walnut Creek as vice-president for engineering research at Arco, while remaining HVEC vice-president for electrical engineering. In other management re-alignments brought on by the merger: HVEC Controller John M. McCarthy has been elected Arco treasurer; George Henderson has joined Arco as business manager; and four HVEC men have been elected to the Arco board of directors (the board totals seven, including three Arco men). Jeppson has become a member of the HVEC Steering Committee.

In the production area, a close liaison has been established between the respective managers. In the irradiation service area, where much is done to encourage and promote industrial interest in radiation, HVEC–Arco is now in a position to "blanket" the country, with irradiation facilities at Burlington; Rockford, Ill.; and at Walnut Creek, where a service linac is available though not now in use.

Civilian Food Irradiation Program Begins With Work at MIT, Gloucester

AEC has selected haddock fillets and shucked clams as the first foods to be investigated in the low-dose, Civilian Food Irradiation Program—the program looking toward substerilization of foods of interest commercially. AEC's Office of Isotope Development, completing several months of planning for this 6-year effort (NU, Apr '60, 31), awarded development contracts on haddock and clams to Massachusetts Institute of Technology ($60,000) and the Gloucester, Mass., Laboratory of the Bureau of Commercial Fisheries, U. S. Interior dept. ($70,000).

Major aim of these complementary inquiries is to determine whether irradiation of haddock and clams, combined with refrigeration (as against freezing), is of practical importance to the fish-marketing industry. Preliminary studies at MIT have indicated that the shipping and storage life of these and several other marine products can be extended from three weeks to four months—permitting expansion of marketing areas and smoothing out the peaks and valleys of supply and demand.

MIT's Department of Food Technology will install the first irradiation facility under the Civilian Program (a 25,000-curie cobalt-60 irradiator designed by Brookhaven National Laboratory). Also, under its AEC contract, MIT will carry out a series of evaluations on haddock and clams, including microbiological evaluation at various dose ranges (100,000–800,000 rads) and acceptability tests on a panel of student tasters.

Under its contract, Gloucester will study the low-level effects of radiation on the essential amino acids and B-vitamins of haddock and clams—over the same dose and temperature ranges (32–34 deg F, 36–40 deg F) as MIT. Gloucester will also study enzyme action, particularly influence on the breakdown of proteins; this lab will also study sensory change (taste, smell, etc.).

AEC was expected to assign its next set of food-irradiation contracts to investigators on the West Coast for studies of flounder and crabmeat. An invitation to fabricate a West Coast irradiator identical to that for MIT was expected to go to industry during December. The Commission also expects to investigate fruit and vegetable irradiation in the program.

MIT Irradiator

The MIT irradiator, designed, fabricated and cold-test-operated at Brookhaven National Laboratory, will be operated by MIT's Food Technology dept., under the supervision of Samuel Goldblith. It will be available to other MIT groups, government agencies, the Gloucester lab and New England fish-processors.

Isotope Surprise at AEC

Surprising support for AEC's Isotope Development Program has developed among the Commissioners. When the fiscal 1962 budget for the Office of Isotope Development was proposed to the Commissioners they decided it was not high enough and tacked on $1-million. Their action came after comments that the use of radiation was one area of the nuclear program already helping the economy —and thus deserved more AEC support. If okayed by the Budget Bureau, AEC's action would give the program a sizeable boost from the current level of $4.25-million.

Nuclear Ship Projects Abroad Beginning to Take Shape

The Symposium on Nuclear Ship Propulsion held Nov. 14–18 at the Sicilian resort of Taormina under the aegis of the International Atomic Energy Agency was probably the best meeting on the subject held yet, in the view of Americans returned from the conference. This judgment is based on their feeling that for the first time other countries had something concrete to say—it was no longer just the U. S. reporting on progress of NS *Savannah*. (The Soviet Union declined to report on its nuclear icebreaker *Lenin*, now completing its first round trip across the northern coast of Siberia, and presented no papers at all. Only Poland and Yugoslavia represented the Soviet-bloc members of IAEA with papers.)

Examples of concrete talk: Germany is entering the hardware stage for its organic-reactor-propelled ship and has been getting fixed-price bids from shipyards for building the vessel. "They seem to have the money to move, with no strings, and don't have the problem of having to select one reactor concept now ["they are planning to try pressurized-water, boiling-water and organic-moderated reactors, with the OMR coming first," one highly-placed American observer commented.].

Likewise, Britain, after long and careful study, is going out on bids for its first nuclear merchant ship, and is expected to make a decision in January. The decision is now expected to favor boiling water.

IAEA sponsored the meeting in cooperation with IMCO, the Intergovernmental Maritime Consultative Organization—newest member of the United Nations' family of specialized agencies. IMCO reported on the International Conference on Safety of Life at Sea, which it had convened this summer in London, and where 55 nations agreed on the general principles of procedure for regulating international traffic in nuclear ships (for example, a safety assessment of a particular ship will be forwarded by the government of the ship's owner to the governments of the countries whose ports the ship is to visit).

Symposium Conclusions

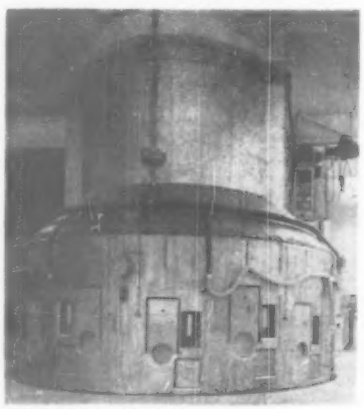
The five-day discussion at Taormina stressed: 1. that it is possible to design a nuclear ship to such safety standards that the risk is acceptable; 2. that no nuclear-propelled merchant ship will be competitive over the next few years; 3. that most of the experience needed can be gathered only under actual seagoing conditions; 4. that it is important to avoid writing restrictive regulations at this time, but instead to amend existing rules as experience grows; and 5. that there is a lot of technical design work still ahead.

The symposium was attended by 179 delegates from 19 countries and six international bodies, and heard 37 papers—of which nine were by Britain, six by Japan, five by the U. S., and one or two each by nine other nations.

Although the Japanese government last year failed to vote funds for the small experimental nuclear research ship planned in 1959, interest continues high. No fewer than 25 nuclear-propelled ships were designed in Japan in the last two years. These are not only paper designs. For example, Kawasaki has used a full-scale, steam-heated reactor model to determine dynamic characteristics, and Mitsubishi built a model reactor vessel to test thermal and residual stresses after pressure and temperature cycling. One Japanese paper reported on a study of the application of vapor suppression for the container of a nuclear ship, based on the U. S. work on this system.

International Projects

The European Nuclear Energy Agency is trying to set up an international nuclear ship project among Europe's maritime nations, quite possibly using the approach it employed so successfully (internationalizing an existing project or one just about to start) in the Halden and Dragon projects and the Eurochemic reprocessing plant. In Europe, besides Britain and Germany, France and Italy are also trying to launch projects —Italy reported on design of a 50,000-ton tanker planned by Fiat and Ansaldo—and Holland, Denmark, Norway and Sweden have also designed nuclear-propelled vessels.



BABCOCK & WILCOX POOL REACTOR in experimental use by a German shipping association in Hamburg (story above)

Germany, France, Italy and Belgium have asked for direct financial aid from Euratom—believed to be a total of about $6-million. Euratom, reacting sympathetically to all four, has already given a commitment to the German organic-moderated project and is expected to aid the French advanced gas reactor, the Fiat-Ansaldo project in Italy, and a Belgian spectrum-shift project.

The Germans are designing their ship (20,000 tons, 570 ft long, 10,000 shp) in such a way that not one but five reactors could be successively tested in it: the original organic-moderated reactor could be removed and four other reactors installed in turn. This could most easily be done by "jumboizing"—cutting out the entire hull section containing the reactor compartment and inserting a new one —as is done today to enlarge conventional tankers. However some observers predict that once the ship is operating well, it will be found easier to build a new hull for another reactor test-bed.

Overall, the German ship reactor development program comprises five projects:

1. An organic reactor, 10,000 shp, for which Interatom (subsidiary of the U. S. firm Atomics International and the German company Demag) has a development order from the Society for Nuclear Energy Utilization in Shipbuilding and Shipping, Hamburg. (This is the reactor that was originally to be installed in the existing tanker *Esso Bolivar*, but will now be put in the 20,000-ton ship on which bids are now being sought; it is, incidentally, left up to the bidder to propose a tanker, freighter or liner.)

2. A pressurized water reactor of 20,000 shp, being developed by Siemens with the Howaldt shipyard.

3. A boiling water reactor providing 20,000 shp, being developed by AEG (prime contractor for the Kahl 10-Mwe central station power plant) with the Deutsche Werft shipyard.

4. An advanced gas-cooled reactor of 20,000 shp, the project of Deutsche Babcock & Wilcox with Blohm & Voss.

5. A high-temperature gas-cooled reactor, 10,000 shp, by the team of Brown Boveri and Krupp (which is building a 10-Mwe central station of such a type—pebble-bed fueled—at Jülich) with the shipyard A. G. Weser.

REACTOR NEWS

DRESDEN SHUT DOWN: CONTROL-ROD DRIVES

The Dresden station was shut down Nov. 15 because of a mechanical mishap—breakage of a tube connecting one of the control-rod poison blades to its drive mechanism—and was expected to remain down for the rest of 1960. The reactor head was removed Nov. 18, the broken rod removed Nov. 21: 3½ ft of the broken 12-ft tube remained attached to the rod, which was pulled out the top, and the remainder of the tube had to be taken out the bottom with the drive mechanism. Examination showed the broken tube had failed due to stress corrosion cracking of its precipitation-hardened stainless steel; a second, unbroken drive tube examined also showed some evidence of cracking. It was therefore decided to replace all 80 tubes with connections of a different alloy. The plant's builder, General Electric, and operator, Commonwealth Edison, emphasized that this was not a recurrence of the old trouble last winter when shear pins inserted in the connection between control rod and rod drive broke (NU, Dec. '59, 25; Jan. '60, 18). That was a mechanical, this a materials problem. GE said radiation was not now a factor as radiation levels in the area of failure are relatively low. There was also good news.

DRESDEN HAD RUN WELL, POWER MAY RISE

Before the mishap, Dresden ran continuously for 27 days, operated above 70% load factor in four weeks of operation after the Oct. 12 dedication. Since beginning power operation it has produced 260-million kwh. Flux peaking has proved to be less, and flux distribution across the core better, than anticipated; these two factors have emboldened GE engineers to believe that the 180-Mwe reactor may be capable of 50% better than design power, or 270 Mwe. So encouraged are they, in fact, that they have already submitted proposals to Commonwealth for adding another turbine and a superheater—possibly nuclear. Edison is only listening, however, has no intention of acting until the plant's behavior and characteristics at 180 Mwe have been thoroughly studied. The present turbine is rated at 192 Mwe gross, may have some additional reserve, but Dresden is presently licensed by AEC only for 630-Mwth, 180-Mwe operation.

PRTR CRITICAL

The Plutonium Recycle Test Reactor at Hanford, designed specifically to test plutonium fuel elements (NU, June '60, 22), went critical Nov. 21.

NEW REACTOR CONTRACTS AWARDED

General Electric has been chosen from among four bidders (others: Babcock & Wilcox, Curtiss-Wright, AMF Atomics) to build a 1-Mwth pool for the **Univ. of Rhode Island** at Saunderstown. GE was third-from-lowest bidder; the State AEC said it gave GE the contract because it felt it would be in the best interests of the State, but did not elaborate . . . Giffels & Rossetti, Inc. of Detroit was picked to be architect-engineer for the Navy's new **Natural Circulation Reactor** in Idaho, which GE is developing . . . Ebasco will be architect engineer for the **Engineering Test Reactor 2**, also in Idaho; Babcock & Wilcox will help design the nuclear portion.

FLUIDIZED-BED EXPERIMENT ASSEMBLED AT MARTIN

Martin Co. has completed assembly of the critical assembly for the Liquid Fluidized Bed Reactor (LFBR), under development for AEC. Criticality was not expected before March, since AEC had still to award a contract for the pea-sized, uranium-dioxide fuel pellets for the assembly. Light water as moderator and coolant will be pumped through a perforated base plate in the cylindrical core—permitting a chain reaction when water pressure forces the pellets apart and stopping the reaction automatically when coolant flow is halted.

SRE TO TRY FOR 1000-DEGREE STEAM

Atomics International, operator of AEC's Sodium Reactor Experiment at Santa Susana, Calif., said it was nearing ready last month to take SRE back to full power with a new core; the plant had been forced to shut down in 1959 when its tetralin moderator leaked into sodium coolant passages, causing fuel meltdown. AI's aim was to heat SRE's sodium to 1200 deg F to produce steady-state steam of 1000 deg F.

HRE-2 CRITICAL AGAIN . . .

Oak Ridge's Homogeneous Reactor Experiment 2, its two holes in the core tank patched (NU, Oct. '60, 28), resumed nuclear operation Nov. 7 at low power, under 1 Mwth, to test the new reversed fuel flow (from top to bottom through the core tank). Oak Ridge hopes this, and removal of flow-diffuser plates from the core tank, have cured the reactor's problems: stagnant areas in the fuel that resulted in local uranium concentrations which burned the holes in the tank wall. They admit the possibility that new holes may develop, but point out that the damage was incurred at relatively low power (~1.5 Mwth), and hope that steady operation at 3–5 Mwth plus the physical changes will show that the hot-spots can be overcome.

. . . AND WTR ALSO

The Westinghouse Test Reactor at Waltz Mill, Pa., down since a fuel element failed in April, returned to operation with a new core-loading Nov. 8, and is now running at full power, 60 Mwth. The master contract with AEC for lease of space went into effect Nov. 15. A second high-pressure experiment loop has been installed.

COLUMBIA UNIV. PLANS A TRIGA

Columbia Univ. will install New York City's first reactor, and its plans are for a Mark II Triga. The General Atomic research unit would be installed in the new Engineering Center at Amsterdam Ave. and 120th St. The Triga would be GA's 21st Triga sale.

FOUR REACTORS GET ACRS GREEN LIGHT

Four reactor projects got favorable reports from the Advisory Committee on Reactor Safeguards: three power units—Elk River, Big Rock Point, Sioux Falls; and the big testing reactor at Plum Brook, Ohio. Elk River and Plum Brook were up for operating licenses; Big Rock Point for a construction permit. Comment on the Sioux Falls reactor, first with integral nuclear superheat, was confined to fuel elements: ACRS approved the proposed substitution of zircaloy-2 for aluminum cladding in the boiling-region elements.

NUCLEAR NAVY NEWS

George Washington, first Polaris-firing A-sub, sailed in mid-November, six weeks early, to take up her patrol station; Defense Secretary Gates said the event "opens a new era in naval warfare." . . . *Ethan Allen*, first of a second generation of Polaris subs, was launched at Electric Boat's yards Nov. 22. . . . *Tullibee* became the 14th A-sub in commission on Nov. 9. . . *Snook* was launched Oct. 31.

WORLD NEWS

First German Power Reactor Critical

The U. S.-built Kahl reactor, West Germany's first power reactor, went critical Nov. 13, and thus also became the first U. S.-exported power reactor to reach completion. The 15-Mwe boiling water unit, supplied by General Electric, is presently licensed by the German government to operate on power levels up to 1 Mwe during its testing program.

Canada Orders Final Design on OCDRE

A $600,000 contract has been awarded to Canadian General Electric for design of OCDRE—Canada's Organic-Cooled Deuterium-moderated Reactor Experiment—by Atomic Energy of Canada Ltd. The contract is an extension of an earlier one, worth the same amount, for preliminary design. The 40-Mwe unit would be the first reactor at Canada's new nuclear research center at Whiteshell near Winnipeg.

French Nuclear Budget Up 13%

France's National Assembly has approved a $253-million appropriation for the 1962 civilian nuclear program, up $60-million over last year. Of the total, $214-million is in direct appropriations, $25-million in loans from the Economic and Social Development Fund advanced for nuclear power stations, and $14-million contributed by the Commissariat à l'Energie Atomique from earned revenue-producing activities such as isotope sales. Three major projects approved for construction start next year include a second plutonium-separation plant at Jobourg near Cherbourg (NU, Oct. '60, 29); a prototype pressurized-water submarine reactor at the new Cadarache reactor research center near Marseille (for which critical experiments have been under way at Saclay since May); and a second pool research reactor, Siloë, for the Grenoble Nuclear Center. Siloë will be considerably larger than the 1.2-Mwth Mélusine pool now operating at Grenoble. In addition to the civilian program, $206-million was approved for the 1961 military nuclear program, including funds for the gaseous diffusion plant at Pierrelatte, part of the financing for the Cadarache submarine prototype, and weapons.

Progress on EDF Reactors

The French National Assembly got a report on the schedule for bringing Electricité de France's three big power reactors at Chinon on the line. EDF-1 is now scheduled to go into service in late 1961, EDF-2 in late 1962, EDF-3 in late 1963. In addition, the SENA reactor that EDF will build with Belgian utilities at Chooz near Givet will go into service in 1965. These four commercial nuclear stations will give France 860–1000 Mwe installed nuclear capacity, not counting the experimental stations of the Commissariat à l'Energie Atomique at Marcoule.

6000 Mw in Europe by 1966 Seen by OEEC

By 1966, nuclear power stations on the line in Europe will total 6000 Mwe, and will account for 5% of total electricity production—with but 3% of the total installed capacity. This is the estimate of a group of experts for the European Nuclear Energy Agency in a report just published in Paris. The estimate is based principally on some 4,509 Mwe of nuclear capacity in operation, under construction, or irrevocably committed as of July 1960. In addition, there was at that time another 3100 Mwe in projects "under active consideration" (type of reactor decided on, bid invitation issued, financing secured, or site under consideration). ENEA made a conservative judgment that 1500 Mwe of this 3100 would be realized by 1966, to reach its estimated total of 6000 Mwe. Capital investment required for this total will be $2.2-billion, the report states. The first 4500 Mwe will cost $1.7-billion; the remaining 1500 Mwe is reckoned at $290-million for 1050 Mwe of natural-uranium reactors at $280/kwe installed, and $110-million for 450 Mwe enriched uranium units at $250/kwe installed—a total of $400-million. Another $100-million should be added, the report says, for unforeseen expenditures on experimental prototype reactors; this brings the total to $2.2-billion. Beyond this, $875-million will be required for fuel costs; roughly $700-million for 15,000 tons of natural uranium and $174-million for 600 tons of enriched. Most of the money will be spent in Europe; the report sees 5000 of the 6000 Mwe accounted for by natural uranium reactors. Purchases of U. S.-built machinery and know-how for the remaining 1000 Mwe in enriched-U reactors should amount to about $75-million, the report says.

India Issues Tarapore Bids

India's AEC has issued its long-awaited bid invitation for its first nuclear power station to be built at Tarapore north of Bombay. It is seeking turnkey proposals for a 300-Mwe station consisting preferably of two 150-Mwe reactors. U. S. firms are apparently being encouraged to bid enriched-U systems, even though India's atom chief Homi J. Bhabha told NUCLEONICS in Washington in November that Tarapore would use enriched U only if bids for natural U were "completely unsatisfactory." A number of U. S. manufacturers are expected to bid, including at least one that has not yet decided whether to propose an enriched reactor such as it is the leader in, or its first natural-U reactor. Very strong competition is expected from firms in Britain, France, Germany, perhaps Japan, and possibly even from the Soviet Union.

No Industry Exhibit at Geneva-3?

A commercial industrial exhibit at the projected third Geneva Atoms-for-Peace conference in 1962 is in doubt, according to sources close to United Nations planning for the meeting. Although the international nuclear industry mounted commercial exhibitions at the 1955 and 1958 Geneva conferences in parallel with U. N.-sponsored scientific exhibitions, objections were raised to doing this again for fear of detracting from the scientific show.

Switzerland, Japan Start up Reactors

"Diorit," **Switzerland's** second research reactor and first domestically-designed one, went critical last month—at long last, having been started in spring 1956 after several years of studies. Diorit is basically a CP-5-type heavy water unit but using natural uranium: the 20-Mwth reactor uses 13,000 lb natural U in 243 fuel elements, and 12 tons D_2O moderator. It will produce about 1.5×10^{13} average thermal neutron flux. . . **Japan** started up and accepted from AMF Atomics her second research reactor, JRR-2, which coincidentally is also a CP-5-type, but using 20%-enriched uranium. Its owner-operator, Japan Atomic Energy Research Institute, agreed to AMF's request that operation be limited with the first core to low-power operation until fuel elements containing inhomogeneities—discovered after the fuel had been accepted—were removed. AMF is standing by its guarantee that "with proper fuel" JRR-2 will operate at 10 Mwth design power on 20%-enriched U.

NEWS IN BRIEF

70 Groups Have Ordered "Citizen Atom" Reprints . . .

Reprints of the "Citizen Atom" Sunday supplement, that appeared in the New York Times on Dec. 11, will run well over 1,045,000 copies, a General Electric official said after its publication (NU, Oct. '60, 22). Half of the copies will be used outside of GE, reprinted without the GE identification or the Times masthead. International GE plans to distribute over 10,000 reprints abroad. Advanced orders—70 in all—at $25 per thousand copies came from governmental and private groups, utilities, companies and universities in response to a September merchandising letter. Orders will be received by GE until Feb. 1 when it will be decide if the number of additional orders warrants a second run.

. . . Union Had Protested Lack of Identification

Earlier, an AFL-CIO attorney in the Fermi case, Benjamin C. Sigal, protested to New York Times officials against one plan for reprinting the supplement; without the GE label, but with the Times masthead and the reprint line: "As printed in the New York Times." Sigal warned an interpretation might be made that the newspaper was taking a side in the Fermi case before the U. S. Supreme Court reached its decision (NU, Dec. '60, 24). He declared: "Reprints without the GE label would, in the absence of internal identification, conceal the fact that it is an advertisement of a company heavily engaged in the atomic energy business and would use the prestige of the New York Times to promote the company's point of view." Now, the reprints will appear in two versions decided upon by the Times and GE: either with the GE label and the Times masthead, or without both. In the blank version, purchasers will be able to insert their own names, if desirable. Most of those already ordered by outside purchasers are in the blank version.

But GE officials said that they and the New York Times officials responsible for the reprints had already acted on their own before knowledge of labor's protest—to cancel a third version: one carrying no external GE identification, but with GE's name on a box inside and the label "As printed in the New York Times." This was done, GE said, after the Times pointed out that this particular version would not "truly" have been exactly "as printed in the New York Times" since there was no external GE advertisement.

N. Y. Ship Asks to Start *Savannah's* Reactor in Camden

The New York Shipbuilding Corp. has formally asked AEC for permission to start N. S. *Savannah's* reactor for dockside operation in Camden, N. J., following core-loading expected this month. Thus, the world's first nuclear merchant ship could make her initial voyage to her sea-trial base in Yorktown, Va., under her own power (NU, Dec. '60, 31). Hydrostatic testing of *Savannah's* reactor has been successfully completed and hydrodynamic tests are scheduled for completion by the end of January.

AEC Asks Comment On Its "Parallel Procedure" Policy

AEC proposes to make official the "parallel procedure" policy it has been using since March 1959. Proposed new regulations would permit public participation during safety-health hearings on those AEC-owned reactor projects planned for (1) non-AEC-owned sites and (2) for use and lease by private electric utilities. In effect, the proposed policy has already been applied to AEC-sponsored reactors at Hallam, Neb., Elk River, Minn., Piqua, Ohio and Punta Higuera, Puerto Rico (BONUS). In addition the proposed regulation requires AEC prime contractors on such projects to obtain the construction permits and operating licenses of its existing regulation and licensing procedures. Comments are invited by AEC until February 1961.

AEC Sets New Charges for Pu for Commercial Use

AEC has set charges for so-called "commercial and industrial" use of plutonium at the same "fair" prices for which AEC buys plutonium from industry. Base charges are used to compute use charges and cost for loss or consumption of plutonium leased by AEC, which, by law, cannot sell plutonium. The "fair" prices and identical base charges are $30–$45/gm (depending on Pu^{240} content) until June 30, 1962 and $30/gm (independent of Pu^{240} content) from July 1, 1962 until June 30, 1963. No schedule has been announced beyond that date. Until midnight December 31, 1960, all uses of plutonium by AEC licensees were deemed research uses for which the base charge was $12/gm. Effective January 1, 1961, all uses of plutonium in instrument components (for example, plutonium-beryllium neutron sources) shall be deemed to be commercial-industrial and the new base charges will apply—even to Pu acquired previously. No base charge has yet been established by the Commission for use of plutonium as fuel for nuclear reactors.

Canadian Uranium Mines Form Research Unit

Six Canadian uranium mining companies, faced with having to close around 1965–66, have formed the Canadian Uranium Research Foundation. Some of many reasons behind the move are: no new markets for uranium are opening up, world uranium overproduction has saturated the market and the nuclear power industry has not grown as fast as anticipated and therefore uses only limited amounts of the metal now. The foundation is already assured by its sponsors of $1,250,000 and expects to spend $250,000 a year on its projects. The foundation's director, Frank Forward, professor of metallurgy at the Univ. of British Columbia, said: "We will try anything to get new ideas for U use."

Battelle Develops High-Temperature Coated Particles

Under a 3-year AEC contract, Battelle will experiment with coating fuel grains about table-salt size to give them high-temperature properties, fission-product-retention capability and good neutron economy. The company has devised a satisfactory way of coating particles using carbon and aluminum for AEC's pebble-bed reactor development program. This concept is attractive to AEC since only nonmetallic refractory materials will be used. Commercially produced fuel particles will also be accepted by Battelle for testing and evaluation under the AEC contract.

15-Mev Van de Graaff Under Design for Los Alamos

High Voltage Engineering Corp. is building and designing its first 15-Mev Van de Graaff accelerator for delivery to Los Alamos Scientific Laboratory. Largest HVEC Van de Graaff so far has been only 12 Mev. The new 15-Mev machine is expected to be operating within three years in a new Multiple Electrostatic Generator (MEG) facility at LASL. The building will also house LASL's present 8-Mev Van de Graaff. LASL plans to operate both accelerators together, producing charges of up to 23 Mev, with particular emphasis on accelerating tritons to 20 Mev to produce neutron-rich isotopes.

RADIATION NEWS

RAI Forms New Irradiated-wire Venture, Reorganizes

After a false start earlier this year (NU, Aug. '60, 26), Radiation Applications, Inc., has gotten together with a new partner to form a company to develop and produce irradiated polyolefin wire and cable: Radiation Materials, Inc. The firm, to be located at RAI headquarters in Long Island City, N. Y., is jointly owned by Loral Electronics, Bronx, N. Y., maker of electronics, wire products and electromechanical relays. Formation of Radiation Materials was one of several major developments at RAI in the past three months. The firm also:

1. Sold 30,305 shares of stock, primarily to fund a new program: development of specialty plastic and chemical materials for the electronics and missiles industries. Under Lawrence Friedman, a new division has been formed around three items already being marketed by RAI—including radiation-grafted teflon tape and film—and this division will also handle irradiated wire, various coatings and compounds, etc.

2. Received U. S. Patent Office approval of the basic patents on its foam-separation process. The firm has begun construction of a pilot unit to explore the commercial feasibility of foam separation for metallurgical and purification processes.

3. Completed an internal reorganization, including creation of a Research div. under Herbert M. Schoen, which will handle all contract research-development. Kenneth Clarke, formerly of Yale, is heading a new nuclear physics section within the Research div.; the section will expand RAI's activities in cosmic-radiation studies, activation analysis and dosimetry. Other section chiefs in the division are George Olean (radiation chemistry), Horace Chandler (materials), and Jacques Weinstock (separations and source technology).

Dublin Joins Martin As Isotopic Power Contractor

AEC said last month that a second contractor—Dublin Industries, San Francisco—was coming into the isotopic power program of the Office of Isotopes Development; the Office sponsors development of civilian applications of such devices, including the strontium-90 weather-station generator to be supplied by Martin Co. to the U. S. Weather Bureau in 1961. AEC selected a proposal of Dublin—as a basis for negotiation—for development and fabrication of a 5-watt test model of a cesium-137 generator and delivery of the model within a year.

Dublin's biggest task will be to raise the specific power of the cesium device as much as possible by concentrating cesium in its "carrier" pellets. "It appears," AEC said, "that they have come up with a compound in which you can put a great deal of cesium." The 5-watt device would contain about 25,000 curies of cesium and weigh less than 300 lb, against nearly a ton for a 5-watt strontium generator.

AEC Breaks Ground on Big Irradiation Facility

Ground was broken Nov. 28 for the $1.8-million High Intensity Radiation Development Laboratory (HIRDL) at Brookhaven, due for completion in January, 1962. HIRDL will use as much as two million curies of cobalt-60 and cesium-137—and spent-fuel elements—as radiation sources; first loading is expected to be about 500,000–600,000 curies. First runs will concentrate on encapsulation of radiation sources, testing of HIRDL's elaborate safety system, studies of small mass heating problems, deep-dose experiments, arrangement of sources on a grid and hazard studies. AEC Isotope Development Director Paul Aebersold, speaking at groundbreaking ceremonies, predicted that Brookhaven, with HIRDL in operation, would "evolve from a major radiation-engineering center of the U. S. into the leading radiation-engineering center of the world."

RDI Negotiating to Establish European Operations

Radiation Dynamics, Inc., said last month it was negotiating with U. S., U. K. and French interests to work out sales and service representation in Western Europe. On the Continent, Westrex div. of Litton Industries is expected to represent RDI in the sale of its radiation machines; talks were still proceeding on establishment of a service center in France, including a 1.5-Mev, 15-kw electron accelerator, in cooperation with a group of French firms. RDI was also negotiating with a British firm for sales and service representation in the U. K.

Pittsburgh Firm Marketing Irradiated Hosp. Trays

Hospital Supply and Development Co., Pittsburgh, Pa., disclosed last month that it had developed disposal surgical trays (with catheters, cotton, etc.,) that it was sterilizing with radiation. The company began marketing the trays Nov. 1, having them irradiated at the service facility of High Voltage Engineering Corp. (*see page 23*). Since then, the company has given Radiation Dynamics (*see item above*) a one-year, 250,000-unit contract to irradiate the trays at RDI's service facility. Hospital Supply said the trays were being marketed through Davol Rubber Co., Providence, R. I., and had met with an immediately good reception. They said radiation was selected for sterilization primarily because there was no other suitable method of sterilizing a product of this kind—one combining plastic and rubber (plastic tray, rubber catheter); an ethylene-oxide gas was considered, they said, but the pressures associated with this approach could not be suitably controlled. HVEC, with other commitments, was not able to schedule their facility to meet Hospital Supply's demand—thus the contract, with RDI, the firm said.

Meanwhile, RDI officials said they were expecting even more substantial business in the medical field in the near future. The firm also said it has completed a new, larger second irradiation vault at its Westbury, L. I., headquarters and would use it initially to test-operate machines on order—before installing its own 3-Mev, 30-kw machine.

Varian Developing Industrial Radiation Machines

Varian Associates disclosed last month that it was developing non-linac radiation machines for the industrial-radiation market (*see page 23*). The machines developed by Varian up to now have been linacs only—for research and radiography, primarily. Varian officials gave no details of the machines under development, except to say they were not linacs and that they would be of low energies (presumably 1-Mev or less). The industrial-radiation-machine market—not substantial as yet—has been dominated by General Electric, with its resonant transformers. However, two other manufacturers—High Voltage Engineering Corp. and Radiation Dynamics—have been developing machines designed to deliver high power at low intensity and cost.

Meanwhile, Varian said: 1. it will deliver this year the first two models of a new medical-therapy machine (6 Mev) to Stanford Univ. and the Univ. of California at Los Angeles; and 2. it has sold the first of a new line of radiography machines to the U. S. Naval Ammunition Depot, Concord, Calif., for inspection of the solid fuel in Polaris missiles.

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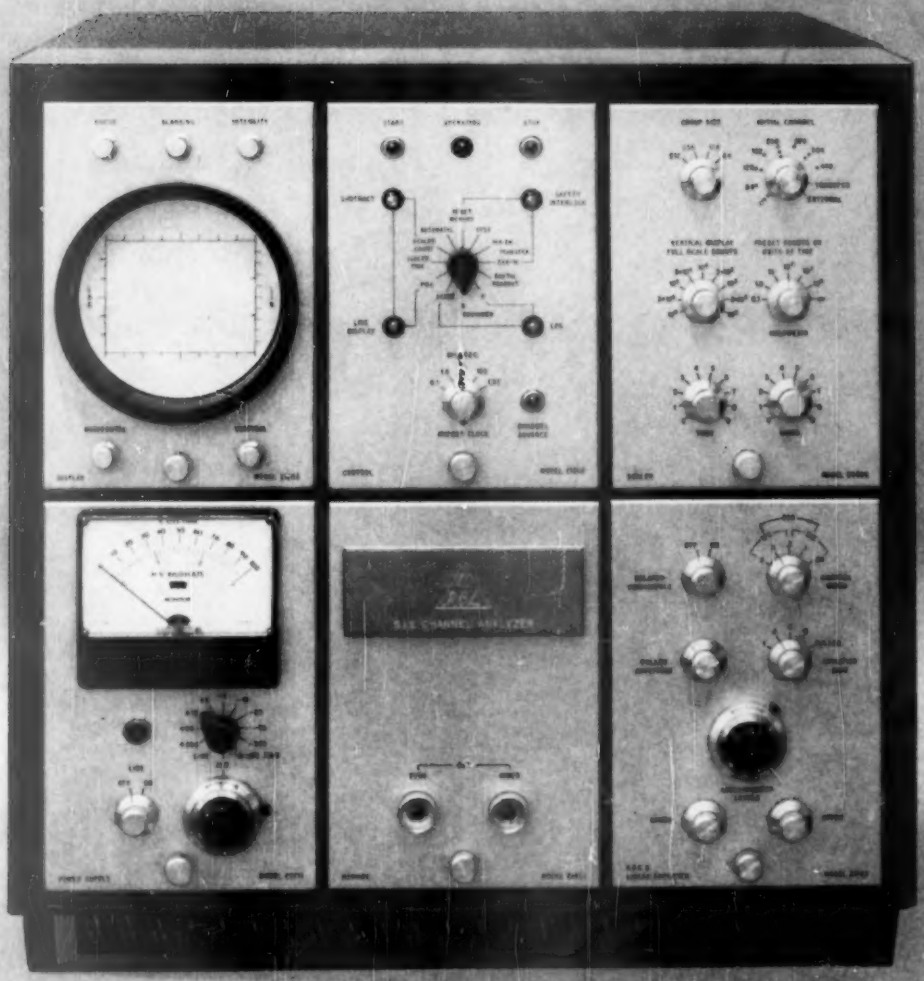

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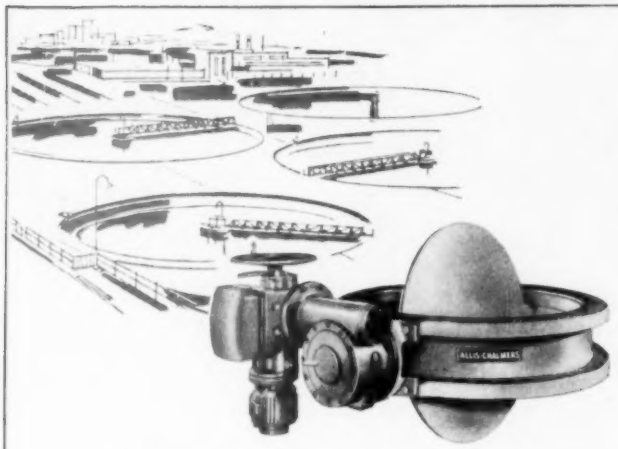

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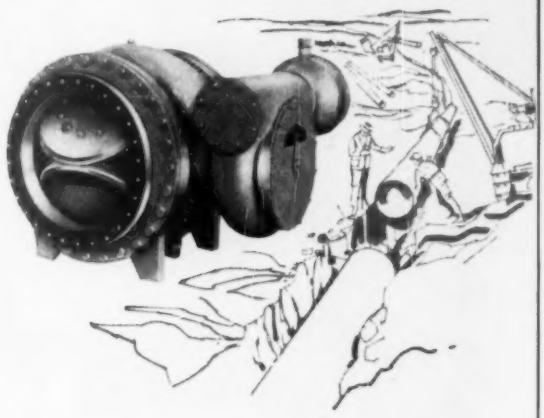

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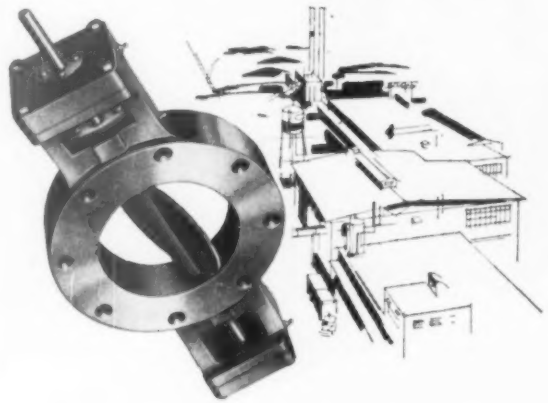

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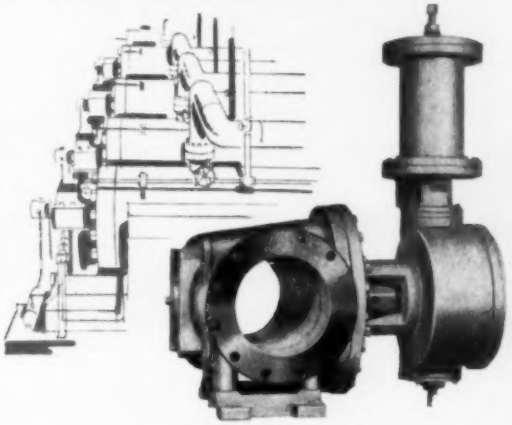

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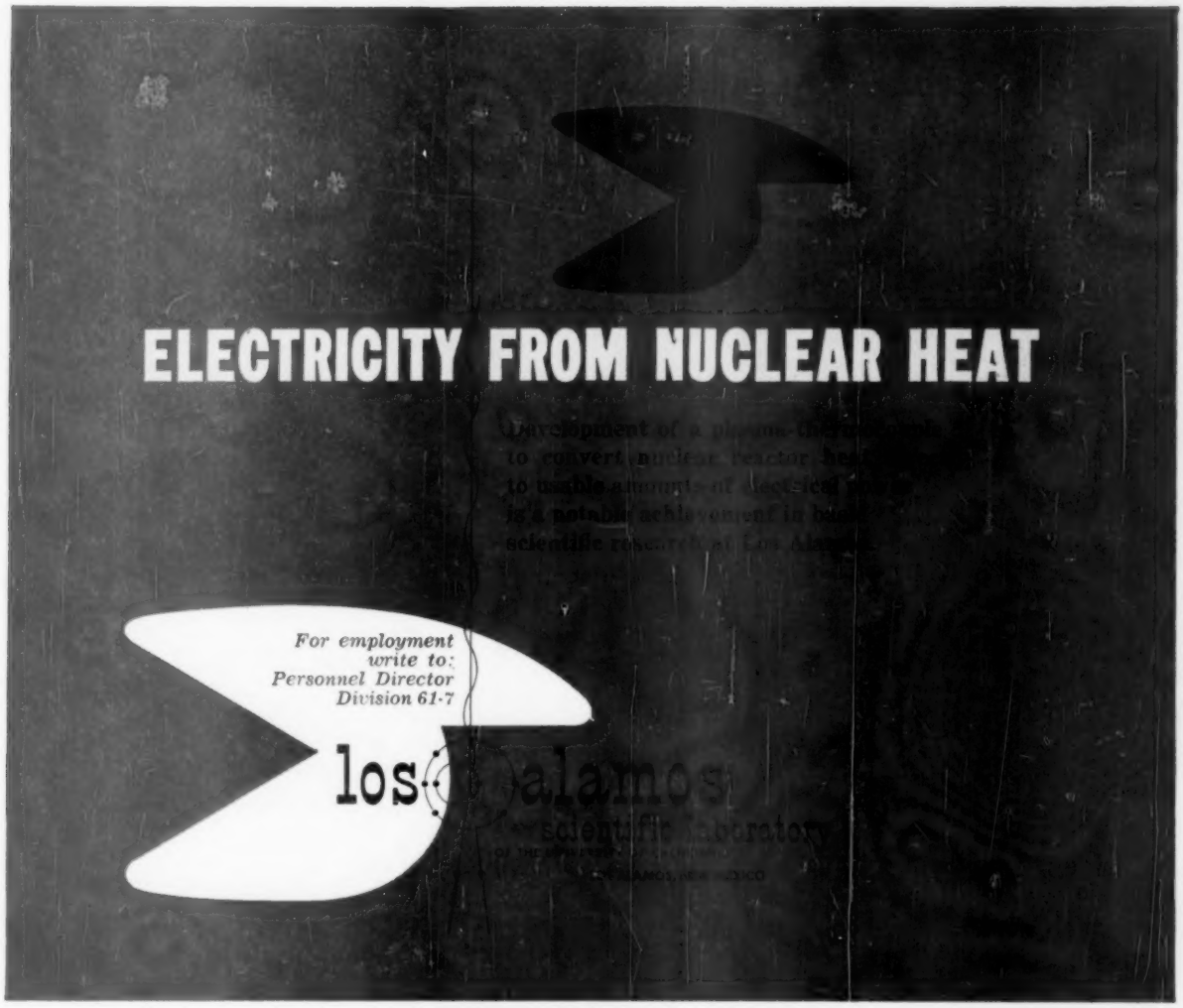
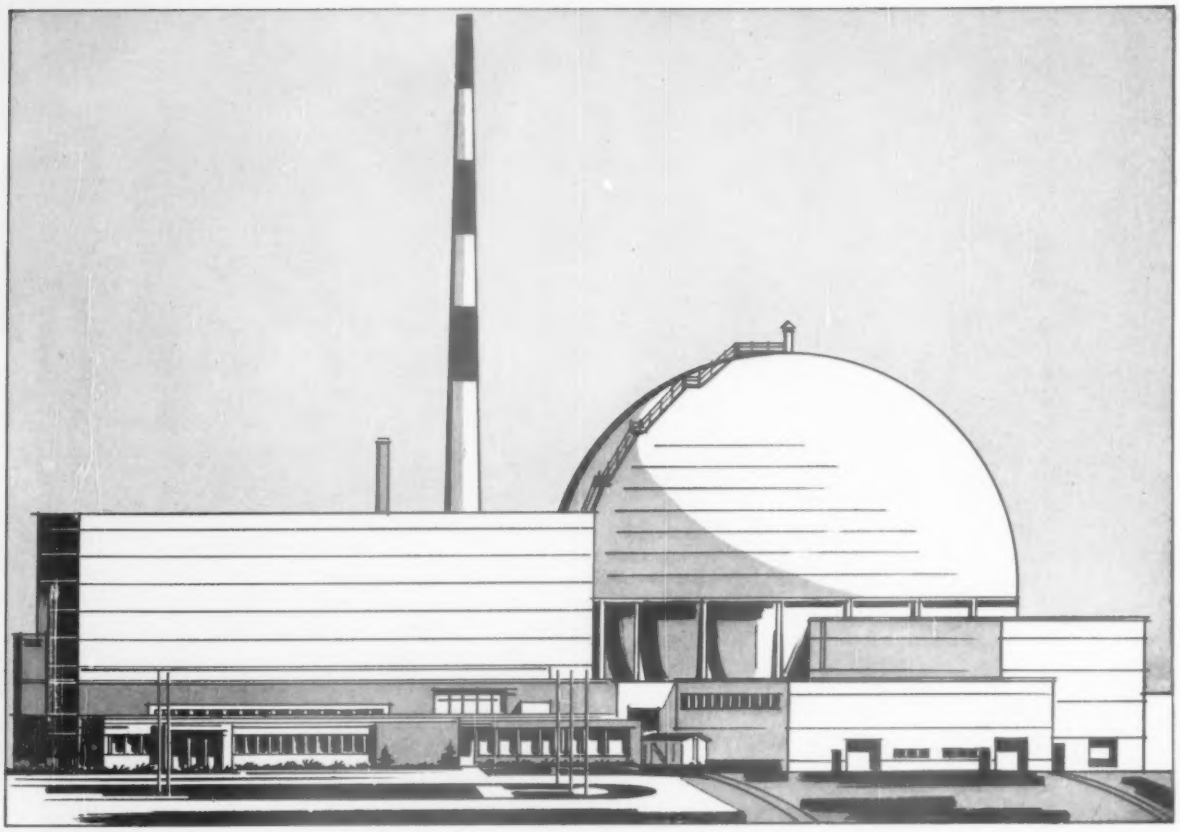


Original painting by Oli Sihvonen, Taos, N. M.



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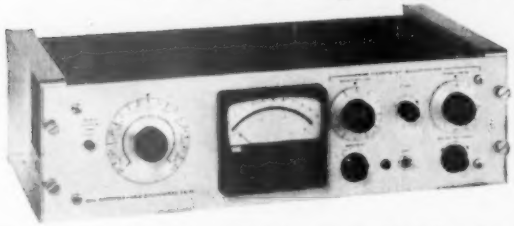

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412/413††	Single 10^{-7} to 10^{-13} amp, source voltage over 1 v.	Within 0.2 decade, with source voltage over 1 v.	Below 0.05 decade in 24 hours with source voltage over 1 v.	Zero at 10^{-13} amp to –6v at 10^{-7} amp; up to 5 ma.
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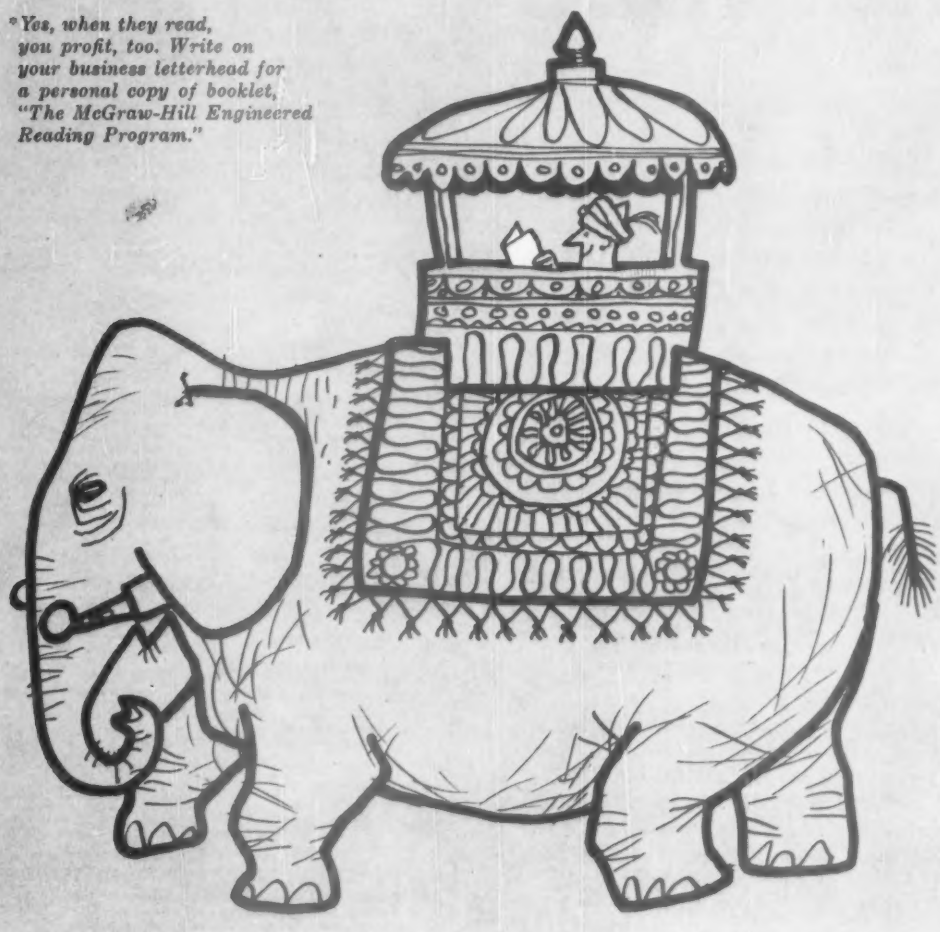

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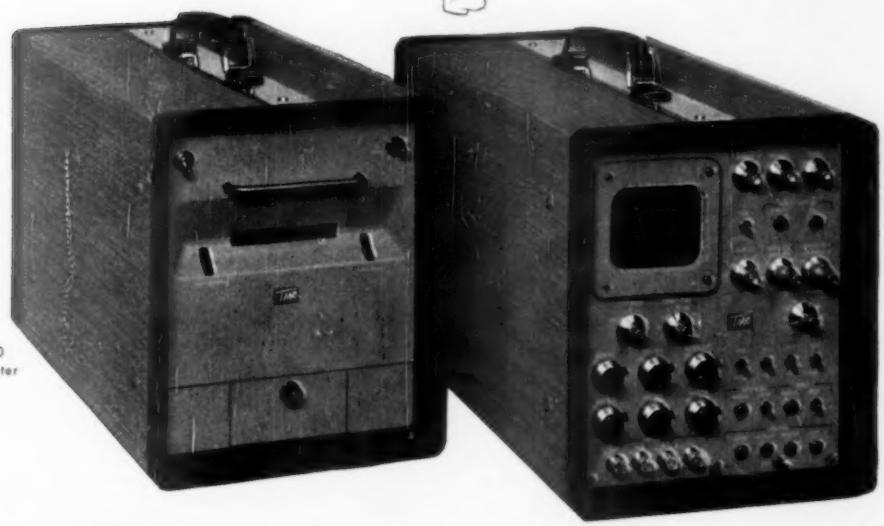

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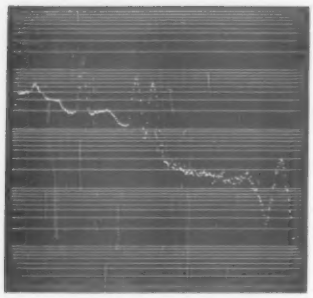

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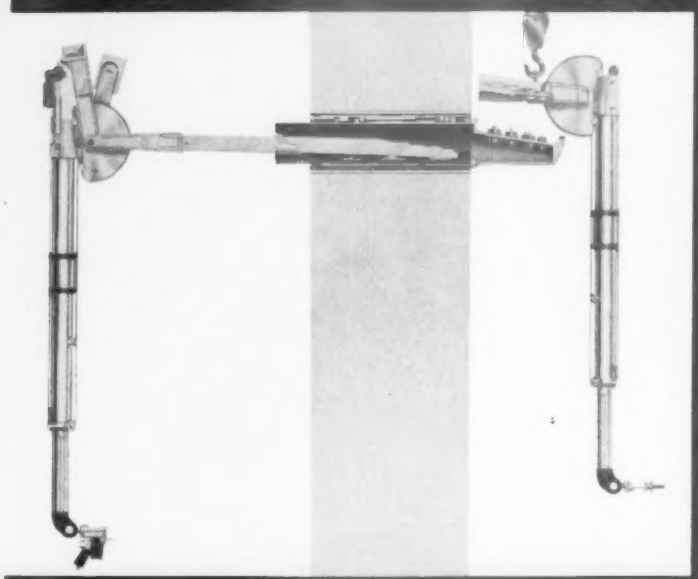

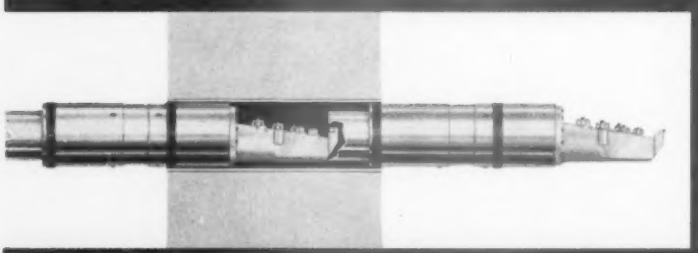

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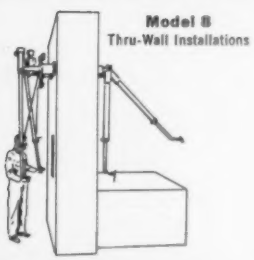

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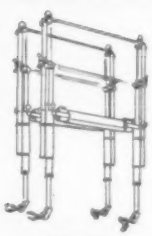

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ANP HTREs Fulfill Test Goals

By GUNNAR THORNTON and BEN BLUMBERG, *General Electric Co., Cincinnati, Ohio*

PERFORMANCE results from the HTRE (Heat Transfer Reactor Experiment) series of tests at the Idaho test station have measured up to or exceeded expectations. Heavily classified until recently, the HTRE power tests have been carried out by General Electric Co. (under AEC and USAF contracts) to demonstrate feasibility of the direct-air-cycle reactor concepts it is developing for the ANP program.

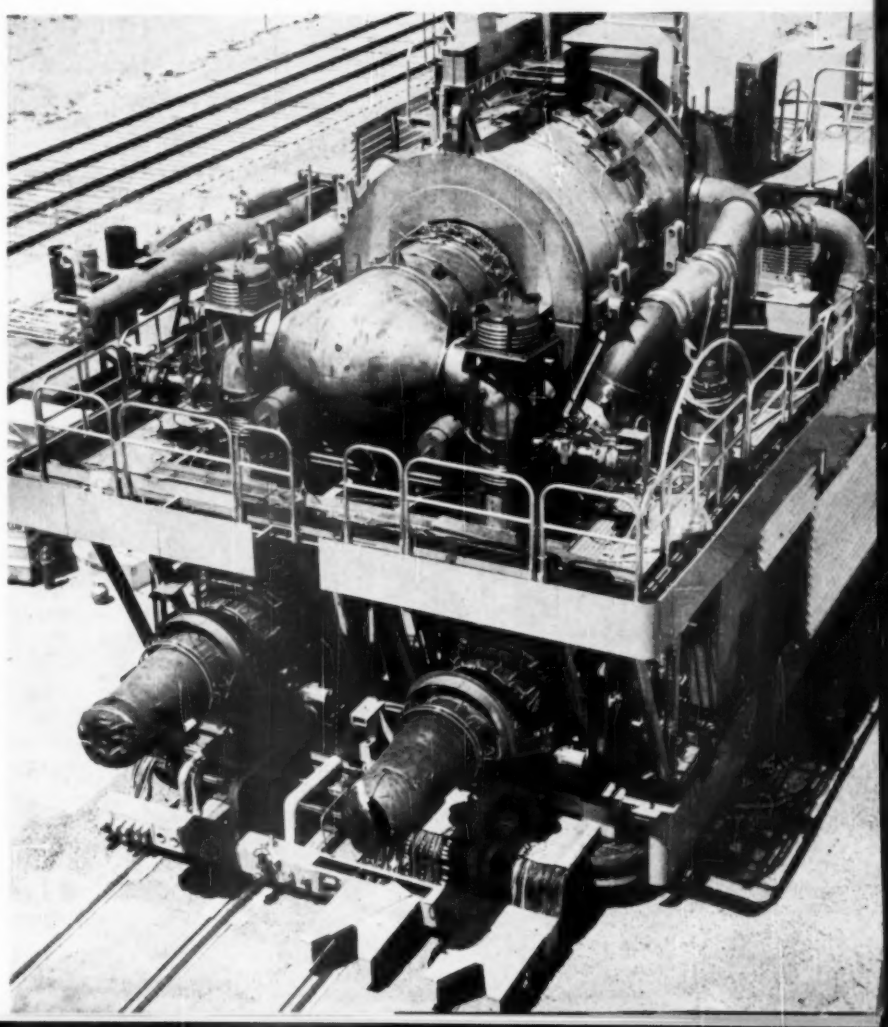
The series has involved three reactor systems (HTRE-1, HTRE-2 and HTRE-3) and two reactor concepts (water-moderated and ZrH-moderated). HTRE-1 was water-moderated with its core-structure water cooled (Fig. 1). It operated a J-47 turbojet on nuclear power only (at power levels up 18.5 Mw). Compressed air from the turbojet was heated directly by Ni-Cr-UO_2 fuel elements as it passed through tubes that pierced the water moderator. HTRE-2 is merely the old HTRE-1 system mechanically modified to serve as a test facility for advanced fuel and moderator sections. HTRE-3, although it has a similar configuration (Fig. 2) and the same fuel material as HTRE-1, differs in that it has a solid moderator (hydrided zirconium) and its core structure is cooled by air. The HTRE-3 system was tested with two J-47 engines in parallel at a 32.4 Mw power level. With higher capacity engines the power levels for the two systems would be correspondingly higher. In both systems the fuel assembly consisted of nests (about 20) of concentric rings stacked in series. (See figure p. 19.)

HTRE-1 achieved a number of full-power runs that demonstrated conclusively the feasibility of operating a jet engine on nuclear power. HTRE-1 easily passed a 100-hr endurance test and ran with its fuel up to 1,850° F.

(Continued on page 46)

Direct-Cycle Achievements Revealed

The curtain of secrecy that has surrounded the ANP (Aircraft Nuclear Propulsion) program for over the last ten years has now been lifted far enough to disclose the technical accomplishments of one of the program's major experimental efforts—the HTRE series of tests, which have been carried out over the last five years on the air-cooled, or direct cycle, reactor concept. In summary, the tests have demonstrated through sustained power runs that a direct-cycle reactor of flyable size can operate successfully as the heat source for conventional turbojet engines. To reach this point the HTRE designers have advanced the art of gas-cooled reactor design to new levels of sophistication. As reflected in the accompanying article, their experiences with new materials, high temperatures and high performance will be of interest to many reactor designers. — EDITORS



HTRE-3, MOST ADVANCED DIRECT CYCLE system operated to date, has powered two J-47s at 30 Mw with air heated to 1,435° F. Same core could power still larger engines

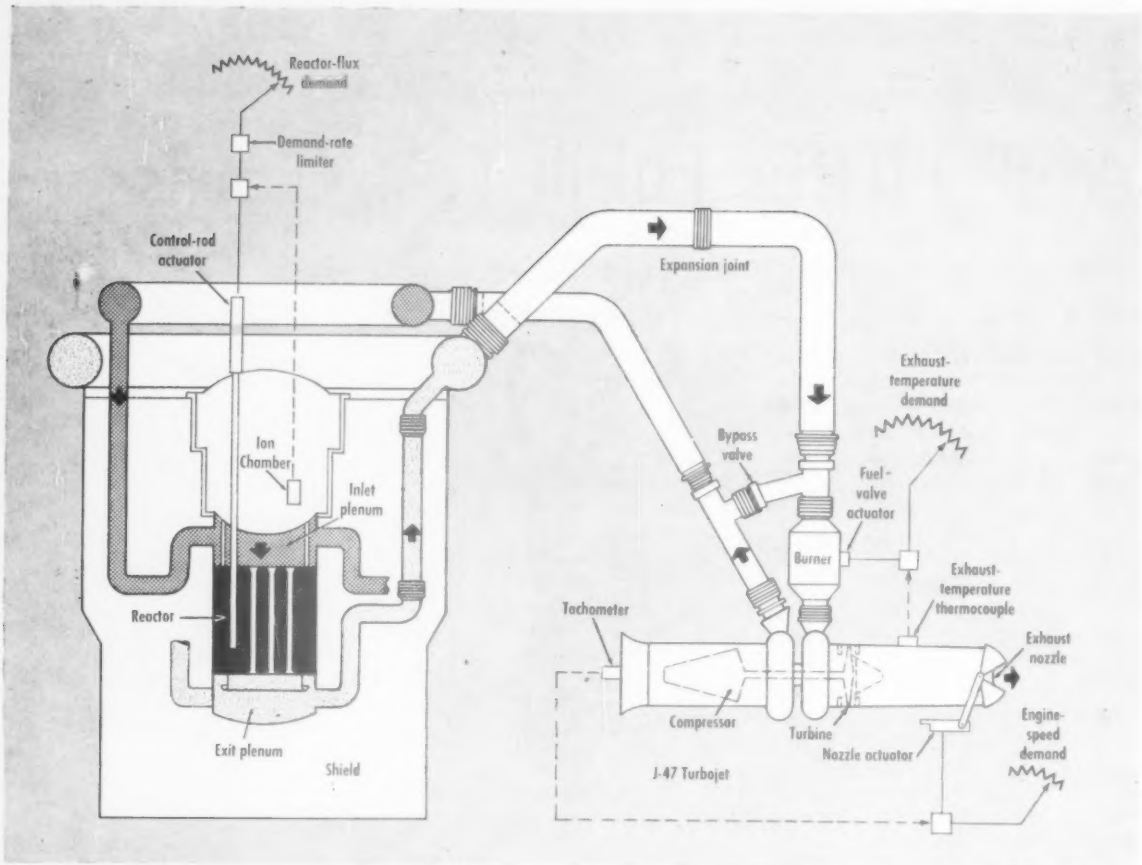


FIG. 1. HTRE-1 SCHEMATIC. In nuclear operation, air enters compressor then goes to reactor to be heated and on to turbine. Chemical burner just above turbine can also be used to heat air either in series with reactor or alone by opening core bypass

The design and testing of HTRE-3 has advanced the direct-cycle program beyond the question of feasibility to the problems of engineering optimization. While this system did not incorporate all of the design refinements now known to be practical and was primarily a "test tool," it is probably the most sophisticated gas-cooled reactor operated to date. A major accomplishment in the HTRE-3 was the demonstration that the power distribution in a reactor can be flattened to ±10%. Designers have also accumulated valuable information on the problems of heat transfer, moderator heating, shield heating, core pressure drop, core lifetime and control. It now appears possible and practical with the technology in hand to build a flyable reactor of the same materials as HTRE-3 and similar in physical size.

With the successful achievement of its test objectives, HTRE-3 is currently taking turns with HTRE-2 (ex-HTRE-1) in further test operations at NRTS.

Although both the HTRE-1 and HTRE-3 systems have reactor cores of about the size needed to fit into an airplane, neither was intended to be the prototype of a flight system. The HTRE-1 reactor was simply suspended vertically in a large shield tank, with no attempt to simulate flight geometry in the shield, support structure, or the ducting systems. The HTRE-3 arrangement, as Fig. 2 shows, more nearly approximates a flyable configuration. In both systems air enters the compressor section of the turbojet engine(s) (HTRE-1 had one J47 turbojet, HTRE-3 has two) and then was ducted to the reactor core. The air passes directly through the reactor core and on to a chemical combustor (in HTRE-1 the air could bypass the core to the combustor through a parallel bypass duct). From the combustor, ducts carry the air back to the turbine section of the turbojet engine(s) and finally to an exhaust stack. The chemical combustor in series with the reactor allows the system to operate at a given power level with the fractional contribution of nuclear power variable between 0 and 100%.

HTRE-3 Design and Operation

The reactor in HTRE-3 operates in a horizontal position with its components supported at each end by Inconel-X tube sheets. The beryllium reflector is made of six equal segments that form a circular container for the active core. The active core contains 150 moderator-fuel units. The moderator is a hydrided zirconium tube with a cross section hexagonal on the outside and circular on the inside (see Fig. 3). An insulation liner between the fuel cartridge and the moderator isolates the fuel elements from the moderator. Both moderator tubes and fuel cartridges are attached to the front tube sheet by remotely operable disconnects and freely supported by the rear tube sheet to allow freedom for thermal expansion.

The active core is 30 in. long and 51 in. in diameter. The core was

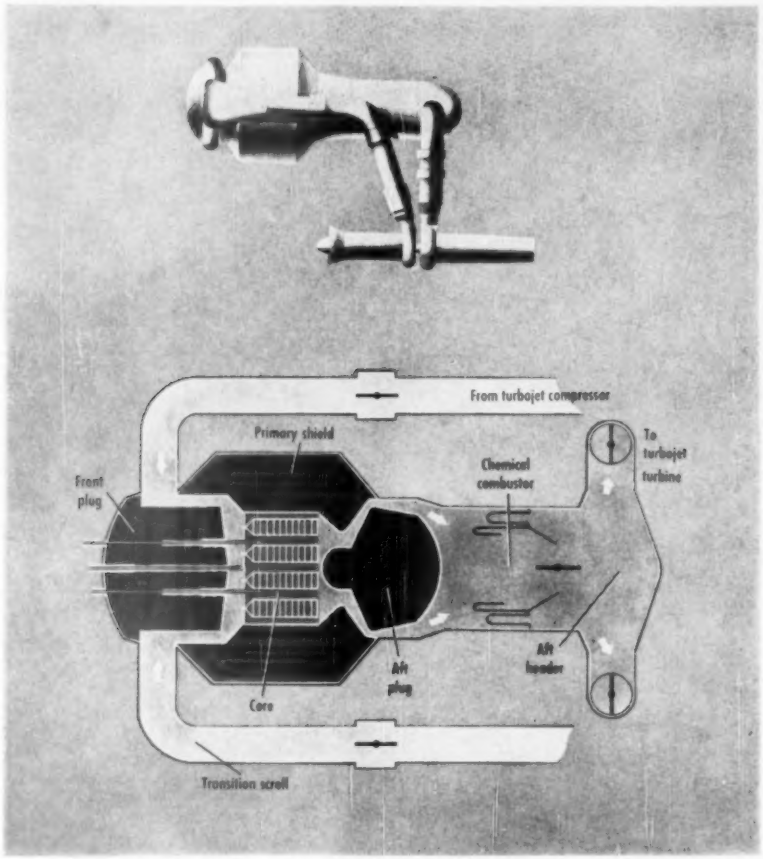


FIG. 2. HTRE-3 SCHEMATIC. More "flyable" than HTRE-1 configuration, system has reactor and chemical combustor joined together in single unit to power two J-47 turbojets

designed to take on air flow up to 850 lb/sec.

It could, therefore, easily handle the combined flow from the two J47 jets of 123 lb/sec to develop a total power of 32.4 Mw. (Were the HTRE-3 core coupled to an engine system that could take fuller advantage of its flow capacity, it could operate at a correspondingly higher power level.)

The reactor is controlled by control rods located at the junction of three moderator cells; the rod inventory includes 30 shim rods, 3 dynamic rods for power changes and 15 safety rods normally out of the core except for shutdown. The arrangement of the control rods and the core's cross section is shown in Figure 3.

The shielding, shown in Fig. 4 is of lead and water. The shields are cooled by circulating the water between the lead slabs and rejecting the heat to a water-to-water heat exchanger on the dolly. The Inconel-X pressure vessel supports the reactor, front plug and rear plug and radial shield.

The beryllium-reflector sectors are composed of hexagonal blocks with longitudinal holes for cooling. With insulation separating the reflector from the active core, the reflector operates at temperatures up to 1,200° F.

Air also cools the moderator tubes through longitudinal slots cut out from the inside diameter. The moderator has operated at temperatures up to 1,300° F for 100 hours without excessive oxidation or hydrogen loss. To accomplish the gross radial power flattening the hydrogen content of the hydrided zirconium moderator tube was varied from tube to tube in the fabrication process.

The control rods are made up of short segments of clad europium oxide held together by straps. This articulated design allows the rod to deflect as required while traversing its guide tube. These rods have operated satisfactorily at temperatures up to 1,600° F in passages offset from the actuator axis by 0.180 in. The rods, with a rate of travel of 5 feet per second and length stroke of 20 inches, have survived 34,000 cycles under varying conditions without failure or malfunction.

The fuel elements are UO_2 in a matrix of 80% Ni-20% Cr and clad with 80% Ni-20% Cr stabilized with niobium. The specific design of the fuel elements is still classified. The fuel elements have operated satisfactorily at temperatures up to 1,900° F for periods in excess of 100 hours.

An automatic system controls neutron flux level from 10^{-4}% to 100% full power, with the 10 to 100% range controlled to ±1% full power. A second system automatically controls temperatures from 1,000° F to 1,600° F ±10° F. The engine speed is automatically controlled by varying the exhaust nozzles to maintain the two turbojet engines at constant conditions while operating with the common heat source.

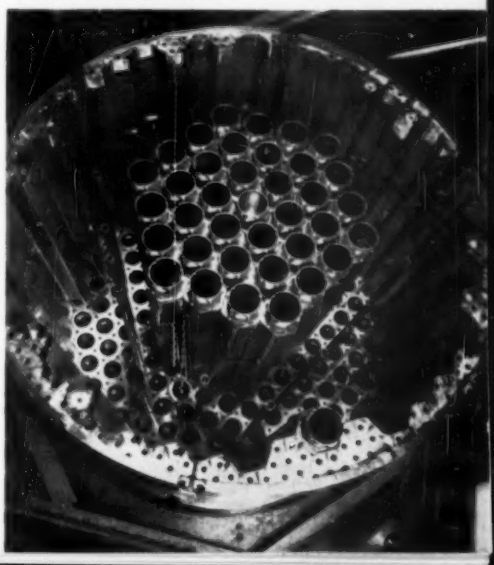
Except for a brief excursion due to nuclear-sensor saturation at the beginning of testing* the reactor performed as predicted throughout the operation of the tests. These tests consisted of a total of 4,935 Mwh with 126 hours at design power (32 Mw). From all indications to date, the remaining core life is several times this amount. A summary of the performance data is given in Table 1.

Design Optimization

Since power output is limited by the maximum permissible temperature of

* Reported in NU Jan. '59, p. 24; GE-ANP will soon release a more complete report on this incident.

FIG. 3. HTRE-3 CORE view shows basic core unit composed of air flow tube surrounded by hexagonal zirconium-hydride moderator. Each tube receives a single fuel cartridge. Small tubes standing alone are control rod guides



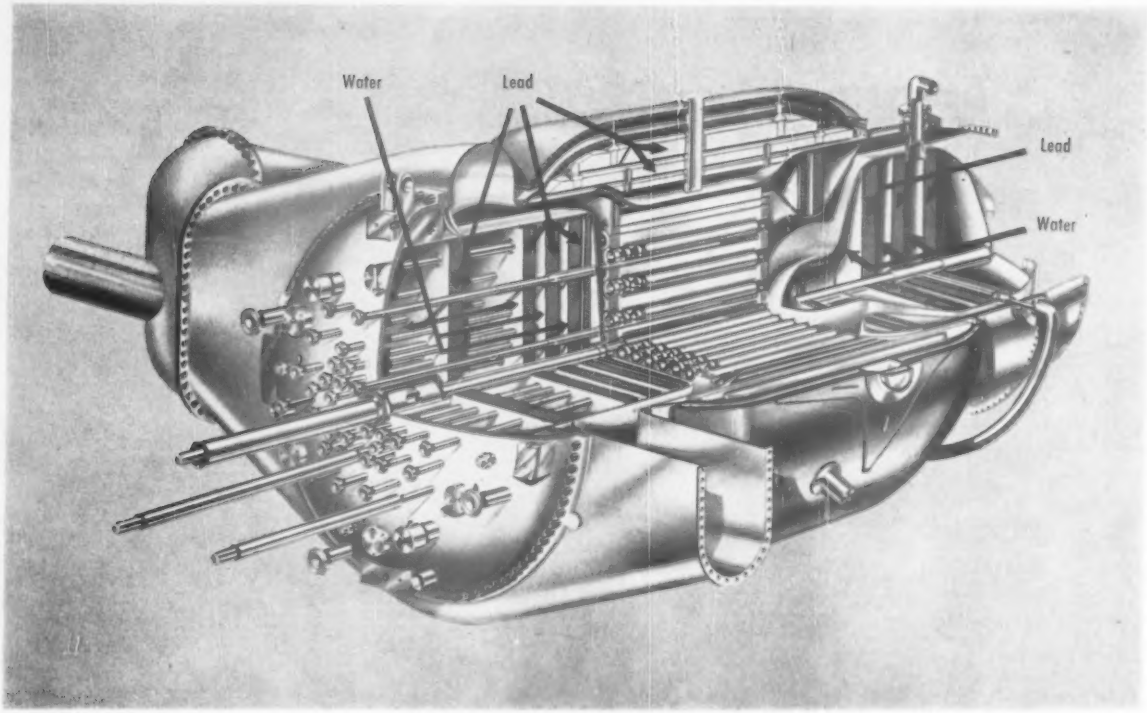


FIG. 4. ARTIST'S CUTAWAY shows lead and water shielding arrangement around HTRE-3 core

the fuel element, over-all power output is increased by making the radial power distribution as uniform as possible throughout the core and adjusting the longitudinal power. This was done in the HTRE-3 by varying the moderator hydrogen content for gross radial control, shimming the fuel elements with boron steel for circumferential power control, extending the moderator beyond the active core for longitudinal power control, and varying fuel loading in individual fuel elements for fine radial power control. While the power distribution in HTRE-3 was adjusted and extensively measured, its control was limited by some features of the design and the time available to modify the design. The goals for this core were merely to demonstrate power-flattening capabilities and to obtain data for making performance predictions.

A temperature survey of the core indicated the maximum air temperature rise through the fuel elements exceeded the average by 17% which corresponds to a peak power sector of 14% greater than the average. Part of this variation is attributed to: (a) intentionally reduced power at the outside of the fuel cartridge because of space variations between the cartridge and the insulation liner, and (b) lower than average power in the center of the cartridge because of manufacturing limitations at that time.

These problems were recognized and subsequent designs offer corrections. Because of these problems a more indicative picture of the core power flattening can be obtained from the maximum power area in the fuel elements, i.e., the area between the inner and outer low power sections. The measured peak temperature rise with one exception did not vary from the average by more than ±8%. The one exception was 12% and this was attributed to the fuel-cartridge and insulation-liner tolerance problem.

TABLE 1—HTRE-3 Performance Data

	Design conditions	
Reactor power to air (Mw)	32.4	
Reactor air flow (lbs/sec)	123	
Turbine inlet air temperature (°F)	1,330	
Compressor discharge temperature (°F)	385	
Compressor discharge pressure (psia)	53.5	
	Predicted	*Measured*
Max. fuel element temperature (°F)	1,880	1,900
Max. moderator temperature (°F)	1,175	1,120
Max. reflector temperature (°F)	1,100	1,030
Max. temperature, discharge air from fuel (°F)	1,640	1,640
Average temperature, discharge air from fuel (°F)	1,430	1,435
Average temperature, discharge air from moderator (°F)	968	880
Average temperature, discharge air from reflector (°F)	955	940
Average temperature, discharge air from control rods (°F)	805	480
Reactor pressure drop (psi)	6.05	6.2
Pressure drop, compressor to turbine (psi)	10.8	9.3

TABLE 2—HTRE-1, Design, Mechanical, Nuclear and Thermodynamic Data

MECHANICAL DATA	
Over-all Reactor Dimensions	
Over-all reactor length (in.)	55.25
Over-all reactor diameter (in.)	59
Number of air passage tubes	37
Tube outside diameter (in.)	4
Tube-wall thickness (in.)	0.080
Fuel Elements	
Active length (in.)	29.13
Outside diameter (in.)	3.432 ± 0.015
Material of meat	UO_2 (93.4% enriched) and modified 80% Ni-20% Cr
Cladding material	Modified 80% Ni-20% Cr
Reflector	
Side reflector	4 in. Be; 12 in. wtr
Dimension across flats, inside (in.)	30.758
End	12.5 in. water-Al matrix
Fuel tube insulation	
Material	Thermoflex RF-1200
Thickness (compressed) (in.)	0.1
Cover material	310 stainless steel
THERMODYNAMIC DATA	
Reactor	
Core inlet air temperature (°F)	359
Core inlet pressure (psia)	54.95
Core exit temperature (mean) (°F)	1,335
Core exit pressure (psia)	47.54
Mass velocity in fuel elements ($lb/ft^2/sec$)	
Core inlet	26.72
Core exit	27.3
Maximum fuel element operating temperature (°F)	1,700 (average)
Total heat transfer area (ft^2)	1,194
Reactor power-to-air (Mw)	15.9
Reactor power-to-water (Mw)	1.6
Total reactor power (Mw)	17.5
Engine	
Compressor pressure ratio	4.95
Altitude at NRTS (ft)	5,000
Air weight flow (lb/sec)	59.5
Compressor discharge temperature (°F)	393
Turbine inlet temperature (°F)	1,295
NUCLEAR DATA	
Uranium inventory (lb)	90 (93.4% enriched)
Burnup (lb)	0.2
Expected cold, clean excess in HTRE ($\%\Delta k/k'$)	3.6
Moderator temperature coefficient ($\%\Delta k/k/°F$)	0.012 (at 140 °F)
Thermal fission-fraction	0.61
Leakage fraction	0.29
Total control-rod value ($\%\Delta k/k$)	9.09 (24 rods)
Total shim-scram value ($\%\Delta k/k$)	7.77 (21 rods)
REACTOR COMPOSITION	
Active Core Dimensions	
Diameter across flats (in.)	30.758
Diameter across corners (in.)	35.516
Volume (ft^3)	13.809
Active Core Volume Fractions	
Water	0.402
Aluminum and insulation	0.0531
80% Ni-20% Cr	0.0576
Uranium (93.4% enriched)	0.00588
Stainless steel	0.000942

In this type of reactor we can define the ratio of the temperature rise from the inlet air to the fuel element surface (ΔT_T) and the air temperature rise through that section of the fuel element (ΔT_b). This ratio $\Delta T_T/\Delta T_b$ is very nearly a constant provided the power distribution in the core does not change. For the HTRE-3 this ratio was found to be 1.23. This ratio could be improved by shifting the power in the fuel element toward the air-inlet end of the reactor (through an increase in the fuel loading in this section) and by increasing the heat transfer area in the downstream stages. While this adjustment was not optimized in the HTRE-3 it was in subsequent designs to give a ratio of 1.17.

These adjustments, however, are not accomplished without paying a price in core pressure drop, which ranks in importance with the turbine-inlet temperature. In the HTRE-3 the methods of predicting pressure drop were verified and subsequent developments in fuel element design have reduced the pressure drop. This reduction provides a greater freedom in optimizing the heat transfer characteristics.

The so-called cooling penalty for the moderator, reflector, control rods and core structure can be easily evaluated by taking the average air temperature rise through the fuel elements and dividing this by the temperature rise through the entire core. These values are found from the performance summary above and give:

$$\Delta T_{Fuel}/\Delta T_c = \frac{1435 - 385}{1330 - 385} = 1.11$$

For the HTRE-3 this shows that cooling (other than the fuel elements) costs approximately 105° F in turbine-inlet temperature. However, the moderator in the HTRE-3, which is the major extra cooling item, was operating considerably below the design value. In addition the moderator volume fraction in the HTRE-3 was 34%, which is greater than required. If this is reduced (by increasing fuel loading or the hydrogen content of the moderator), the cooling flow would be reduced approximately in direct proportion.

While the absolute performance of this system was limited by a not too optimum design, the data obtained show that a higher performance system can be produced with the technology now available. The following is a simplified extrapolation from the HTRE-3 data to such a system.

Consider the following relationships:

	HTRE-3	*Modified Design*
$\Delta T_b'/\Delta T_b$	1.17	1.10
$\Delta T_b/\Delta T_c$	1.11	1.09 for $T_c = 1550$
		1.11 for $T_c = 1650$
$\Delta T_T'/\Delta T_b'$	1.23	1.17

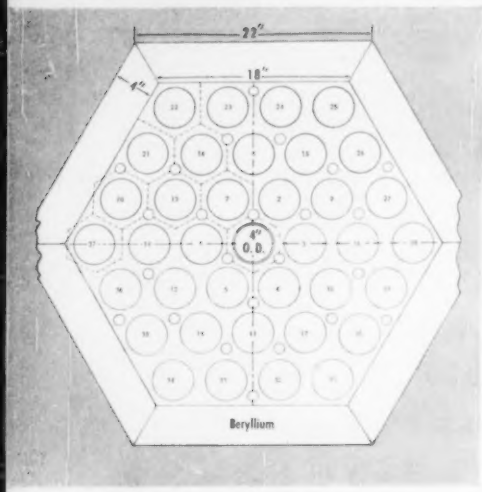


FIG. 5. HTRE-1 CORE arrangement involves six unique cell configurations e.g. cells 1, 7, 23, 14, 21 and 22

Here the *primes* refer to peak temperature.

- $\Delta T_b'/\Delta T_b$ is basically a peak to average power ratio in the fuel elements.
- $\Delta T_b/\Delta T_c$ is the penalty for core components other than the fuel elements.
- $\Delta T_T'/\Delta T_b'$ depends on the heat transfer characteristics of the system.

In terms of these ratios the maximum fuel element is

$$T_e' = \Delta T_c \left(\frac{\Delta T_b \, \Delta T_b' \, \Delta T_T'}{\Delta T_c \, \Delta T_b \, \Delta T_b'} \right) + T_i$$

Figure 6 shows a plot of this equation for the improved reactor design. The modified design assumes a core inlet temperature $T_i = 700°$ F and an increase in the moderator temperature to an average of 1,150° F and a reduction in the moderator volume fraction from 34% to 24%.

With the materials used in the HTRE-3, this design could then have an exit air temperature of 1,500–1,650° F. The exact air temperature would depend on the operating time desired—1,000 hr for 1,500° F and 25 hr for 1,650° F.

In summary the performance of the HTRE-3 has demonstrated that a system using the same materials can be designed which would power a modern gas-turbine power plant. The reactor would have a size, pressure drop and power capability compatible with flight requirements. Advanced materials will extend this performance but flight is possible and practical with the technology now in hand.

HTRE-1 Description

In the HTRE-1 reactor unpressurized water at 160° served as both moderator and structural coolant. The reactor structure was fabricated of aluminum and consisted of a cylindrical water vessel penetrated by 37 four-in. dia tubes in a hexagonal pattern with radially varying spacing. The reactor air flowed through three tubes each of which contained a fuel cartridge. The tubes were lined on the inner surface with a thin sleeve of stainless-steel-jacketed, mineral-wool felt insulation to reduce heat flow into the water moderator.

Tube sheets at each end of its tube bank joined with a cylindrical shell to form a water-tight tank 59 in. in dia and 55 in. long. This reactor tank also contained the reflector—beryllium slabs four inches thick, spaced $\frac{5}{8}$ inches from the outside tubes and supported from brackets welded to the tube sheets. The control rod guide tubes, welded into the top tube sheet, performed double duty as inlet tubes for moderator water. The water moderator filled the entire reactor vessel except the air passages. After picking up heat from the beryllium reflector and aluminum structure, the water circulated to an external radiator.

The fuel cartridges were made of an 80% Ni-20% Cr alloy impregnated with UO_2. Each fuel cartridge had a loaded length of 29.125 in. The unloaded air tube and water matrix extended beyond each end of the active core to serve as the end reflector. The core volume fractions shown in Table 2 were computed for a total core volume defined by the inside surface of the beryllium reflector.

The gross radial power was equalized from tube to tube by varying the spacing of the tubes. Figure 5 shows the six unique cell configurations (e. g. tubes 1, 2, 9, 15, 25, 26) that defined the core geometry. Near the outside of the reactor, where the power would normally be low, the tube spacing was increased. Thus more moderator was associated with each tube and the thermal flux between tubes was made equal. The beryllium reflector was also important in maintaining a sufficiently high flux in the outer tubes. An important feature of this method of power flattening is that all fuel cartridges can be identical, making for simple fabrication.

The fine radial power distribution was flattened within a fuel cartridge by radial variation in the fuel loading within the cartridge. Since the fuel loading was uniform in its longitudinal direction, the reactor had the conventional longitudinal "cosine" power distribution.

The basic scheme of controlling the HTRE-1 power system was similar to that of HTRE-3. The power system was started on chemical fuel alone with compressor air passing through the cold reactor. Then, the reactor was started and nuclear power was increased. When the nuclear heat added to the air detected as an increase in air temperature by the turbine exhaust thermocouple, the chemical fuel valve would start to close in an attempt to maintain the exhaust temperature at the predetermined level. As the reactor power was further increased, the chemical fuel would shut off completely so that operation was completely on nuclear power.

HTRE-1 Operation

During its life time HTRE-1 underwent three series of power tests (designated IET #3, #4, and #6) at its Idaho Test Station starting December 27, 1955 and ending January 3, 1957.

IET #3. The first series of operational tests succeeded in operating exclusively on reactor energy at power levels from ~0 to 16.9 megawatts. After about 6 hours of accumulated operation at full nuclear power, the reactor was returned to the hot shop, to check the possibility of fuel element damage as indicated by the exit air-radioactivity monitors. Examination of the fuel cartridges revealed that several cartridges were damaged, with segments of the fuel elements partially melted or oxidized. The damage resulted from differential air pressure across the insulation sleeve between the fuel cartridge and the wall of the air tube. The pressure differential had caused the insulation sleeve to collapse against the fuel cartridge restricting airflow and preventing adequate cooling of the outer fuel surface.

Except for the insulation liners, system components generally performed in good to excellent agreement with design predictions. The observed distribution of fuel element temperatures and the maximum value of selected fuel element temperatures were greater than anticipated, due apparently to high temperatures near the damaged regions.

The reactor core was reassembled with 24 of the original fuel cartridges and a new set of insulation liners partially redesigned to provide pressure relief.

IET #4. The second series of power tests (IET #4) with the modified insulation liners showed no significant deviations from the results of the first tests. The system was again shut down for disassembly and inspection in the hot shop—this time to determine whether any further design modifications were necessary for the final endurance run. The test operation and post-examination indicated that the insulation sleeve redesign was not completely successful in that damage had still occurred to one fuel cartridge.

During the IET #4 series, the reactor operated a total of 1,877 megawatt-hours at a maximum sustained power level of 16.0 megawatts-to-air. Partial chemical heat was supplied during the entire IET #4 operation. The maximum core discharge temperature was 1,394° F. The total operating time at a power-to-air of 16 megawatts was 84 hours.

IET #6. The last power series (IET #6) used redesigned and reinforced insulation liners together with a complete set of virgin fuel elements. In low power tests, at the start of the series, it was found possible to operate the reactor with a temperature-rise across the core three times the inlet temperature; there were no indications of the flow maldistribution or instability that had been considered possible for this low-flow condition.

A two-phase all-nuclear endurance testing program was formulated for IET #6. In phase A the reactor was required to demonstrate 100 hours of engine operation on full nuclear power at a core discharge temperature of 1,280° F and thus meet the primary endurance demonstration objective. This the reactor accomplished without incident. For Phase B, the reactor exit-air temperature was raised to 1,380° F, which corresponds to a maximum fuel element temperature of 1,850° F, and was 150° F in excess of the design point. After 39 hours at these conditions the system was returned to the hot shop for examination.

Post-operation observation of the fuel element indicated no gross oxidation or melting as observed during previous operations, indicating that the insulation liner redesign was successful.

HTRE-2 Facility

HTRE-2, the second designation of the experimental series, is the name that was bestowed upon HTRE-1 after the reactor was modified to accomodate special test specimens of more advanced fuel element and moderator assemblies. The facility has made possible tests that could not be performed in ordinary in-pile experiments. In HTRE-2 the core was the same as it had been in HTRE-1 except that the central seven air tubes were removed and replaced by a hexagonal void (see Fig. 7). Sections of advanced reactors were inserted into the "parent core" through an opening in the top shield plug and were cooled by air drawn from the common plenum chamber above the reactor.

After HTRE-2 accumulated 552 hours at test power levels, 20 of the 25 fuel cartridges were replaced in the parent core to restore the margin of reactivity. The fuel elements themselves appeared to be metallurgically and mechanically in good condition and capable of operation for an indefinitely longer period if reinstalled into a reactor of greater excess reactivity margin.

In summary, the HTRE-2 parent core has operated for an accumulated total of 992 hours with fuel element temperature between 1,200 and 1,750° F and reactor exit air temperature between 875° F and 1,125° F. Five of the fuel cartridges have served for the entire 992 hours with no external manifestation of metallurgical or mechanical difficulties.

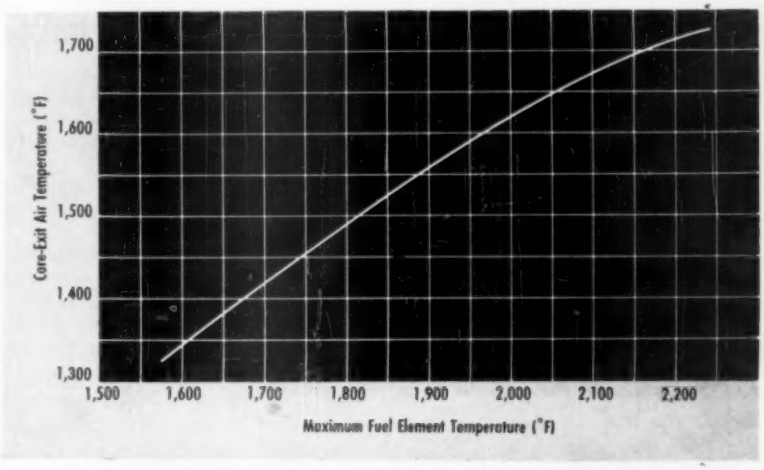
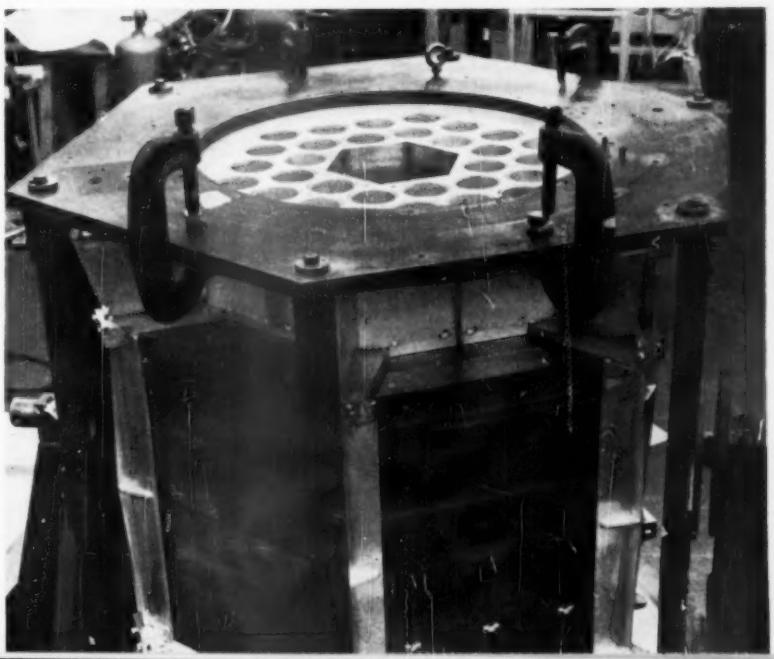


FIG. 6. AIR TEMPERATURE at core exit vs. maximum fuel surface temperature in core for optimized design extrapolated from HTRE-3 data. Air-inlet temperature = 700° F

FIG. 7. HTRE-2 used to test advanced reactor components in central void shown in core was built from old HTRE-1 after it had finished test series



What is the Mössbauer Effect?

1 **FREE-ATOM RECOIL** reduces photon energy. When absorption takes place, corresponding recoil increases energy of absorption

2 **RECOIL UNCERTAINTY** comes, in gases, from randomness of atom velocities, in solids from excitation of vibration quanta (phonons)

3 **MÖSSBAUER EFFECT** requires zero-phonon emission (and absorption). Entire crystal recoils, and photon takes most of energy

The Mössbauer Effect:

When a whole crystal, rather than an atom, absorbs gamma recoil, tiny line widths permit measurements of gravitational red shift, nuclear-level splitting and many solid-state effects

By GUNTHER K. WERTHEIM, *Bell Telephone Laboratories, Murray Hill, New Jersey*

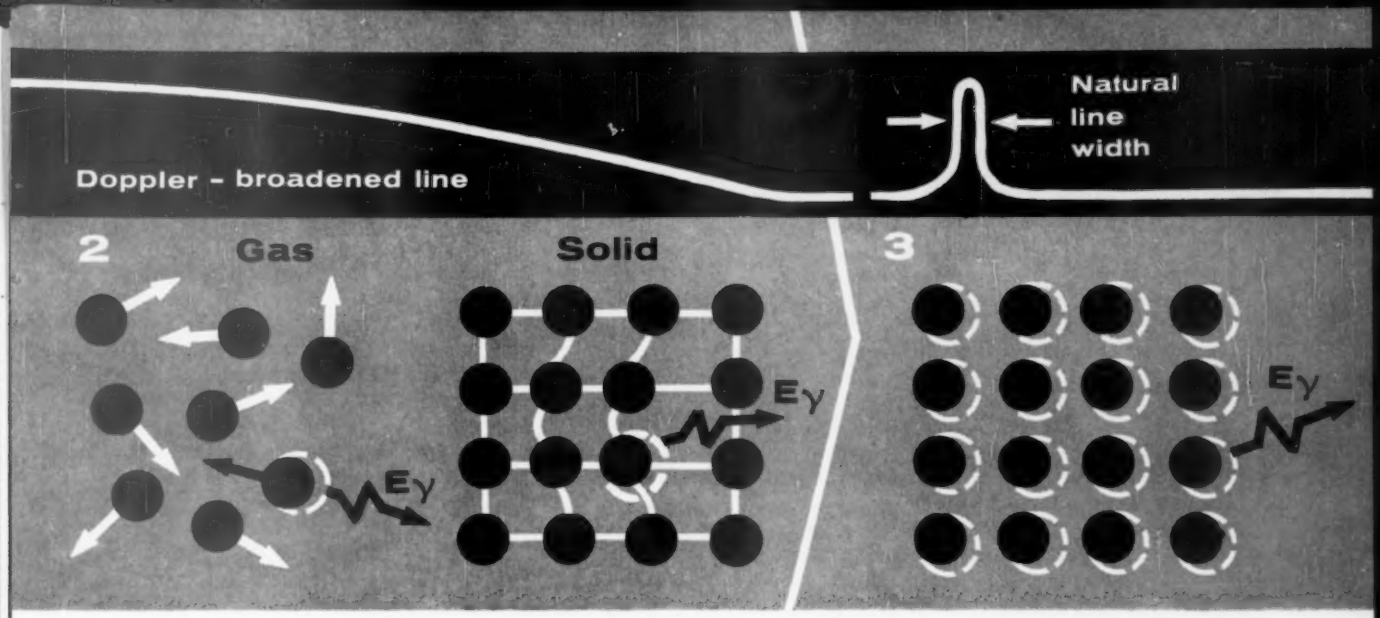
GREAT MOMENTS in physics occur when universally accepted "self-evident" ideas are shown to be false. A well established concept recently overthrown was that any atom that emits a gamma photon must recoil so that momentum is conserved. This is not to say that the law of conservation of momentum has joined the law of conservation of parity in the discard pile; it is rather that if the emitting atom is bound in a solid, it can be the solid as a whole, rather than the individual atom, that recoils. Since momentum is conserved, the energy taken up by the crystal is in the ratio of the mass of the photon to twice the mass of the crystal.

When the uncertainty of recoil energy is removed from gamma emission and absorption, gamma-ray line widths become so narrow as to make possible many experiments undreamed of a few years ago. Typically the line width is reduced by a factor of 10^6. With such narrow lines one can see the Doppler shift introduced by the speed of the tip of the minute hand on a small clock. Another energy shift that has already been measured is that of a photon moving from a point of greater gravitational potential to one of lower potential—all within the same physics laboratory. The technique has significant applications in nuclear spectroscopy and many more, most of them still untried, in solid-state physics.

What Is the Effect?

The significance of recoil-free gamma emission is that the resulting gamma photons have an energy almost exactly equal to the nuclear transition energy; the uncertainty in energy depends only on the lifetime of the excited nuclear state. It is readily possible to find nuclides for which the fractional uncertainty in the gamma-ray energy is as little as 1 part in 10^{12} or 10^{13}. The energy (and hence the frequency) of these gamma rays is more accurately defined by several orders of magnitude than radiation produced by a maser, previously the most accurate frequency standard available. Fortunately the inverse process, recoil-free absorption, is also observed and makes possible an equally selective detector for these highly monochromatic rays. The combination of the two processes constitutes what is now called nuclear-resonance scattering or the Mössbauer effect (after its discoverer R. L. Mössbauer). Most of its applications make use of the extreme selectivity of the effect, which enables experimenters to detect very small changes in the gamma-ray energy due to such processes as the gravitational red shift or nuclear hyperfine splitting. Before discussing these applications further, let us look into the resonance scattering in greater detail.

Resonance scattering of electromagnetic radiation from the outer electrons of atoms is easily observed; the familiar lecture demonstration is fluorescence of sodium vapor excited by sodium D lines. The analogous nuclear process was long thought to be much more difficult to demonstrate since it was considered obvious that the emission of a nuclear gamma photon by an atom was always accompanied by a nuclear recoil (see figure above). This recoil generally takes up an amount of energy greater than the natural line width of the nuclear state. Absorption, on the other hand, requires that the gamma-ray energy be larger than the nuclear transition energy by the same recoil energy. The emission line is therefore



A Tool for Science

displaced from the absorption line by twice the recoil energy.

Before 1958 nuclear-resonance scattering had been demonstrated in three different ways: (a) by placing the emitting atoms on a high-speed centrifuge and using the resulting Doppler shift to compensate for recoil loss (*1*, *2*), (b) by working at very high temperatures in gases so that the Doppler broadening of the emission and absorption lines becomes comparable to the recoil loss (*3*), and (c) by using the motion that the emitting atom might have as the result of a preceding nuclear process such as gamma emission or beta decay (*4–7*). In all three of these situations the gamma-ray line width is much greater than the natural widths of the nuclear states involved in the transition.

These statements about recoil energy loss apply strictly only to free atoms. In atoms bound in solids, when the recoil energy is so small that the structure of the solid is not disturbed, the recoil of an atom that emits a gamma ray is restricted to the emission or absorption of lattice phonons, vibration quanta (see figure above, 2). The average energy transmitted to the lattice, when many events are considered, is still the free-atom recoil energy, but an individual event may involve zero, one or many phonons. This is also true of absorption.

Recoil Absorption

The realization that such zero-phonon processes exist constitutes the essential discovery of R. L. Mössbauer (*8*), the young German physicist whose investigations, reported in 1958, made possible the development of a technique that has already found applications in an amazing variety of fields. In a zero-phonon process, momentum conservation is satisfied by the recoil of the crystal as a whole, and the large mass of the recoiling entity makes the recoil energy loss negligibly small. The emitted gamma quantum has the full energy of the nuclear transition and can be resonantly absorbed in a similar recoil-free process (see 3 above).

The fraction of zero-phonon processes in either emission or absorption depends on the ratio of the free-atom recoil energy E_r to the lattice vibration energy $k\theta_D$; when the ratio is small, relatively many zero-phonon processes take place. There is also an explicit temperature dependence that reduces the fraction of zero-phonon processes at high temperature. The exact expression for the fraction of zero-phonon processes is

$$f = \exp\left[-\frac{3E_r}{2k\theta_D}\left(1 + \frac{2\pi^2 T^2}{3\ \theta_D{}^2}\right)\right] \quad (1)$$

(θ_D is the Debye temperature characteristic of the solid; T is absolute temperature; k is Boltzmann's constant). By the choice of a nuclide in which recoil energy is much smaller than lattice-vibration energy, situations have been created in which more than two thirds of the events are recoil free.

The preceding equation is applicable only when the phonon spectrum of the solid can be characterized by the Debye temperature. It does not apply to the more interesting situation when the emitting atom is present as an impurity in a foreign host lattice. In this situation the phonon spectrum in the neighborhood of the impurity atom is modified by localized modes that reflect both the binding of the impurity atom and the mass ratio of the impurity atom to the host lattice atom. Hence the fraction emitted without recoil reflects not the normal lattice-vibration spectrum, but rather the complex situation in the environment of the impurity.

Experimental Demonstration

Mössbauer first observed resonance absorption while measuring the temperature dependence of the scattering cross section of iridium for Ir^{191} gamma rays. He found an increase in absorption at low temperatures, at which processes then known predict a decrease. The observed behavior follows from the increase in the number of gamma rays emitted without recoil as the temperature is decreased (Eq. 1). The proof that the process under observation was resonance scattering was obtained by comparing the cross sections of an iridium and a platinum absorber for gamma rays emitted by Ir^{191}. The excess absorption was found only in the iridium absorber.

This effect, the Mössbauer effect, is readily observable even when the fraction of gamma rays emitted without

recoil is only a few per cent, since the resonance cross section is very much larger than that for other scattering processes. This cross section is

$$\sigma = 2\pi\lambda^2 \frac{1 + 2I_e}{1 + 2I_g} \frac{1}{1 + \alpha} \qquad (2)$$

(I_e and I_g are nuclear spins of excited and ground states; α is internal conversion coefficient). For Fe^{57}, which has found much favor for Mössbauer scattering experiments, the resonance cross section is 1.5×10^{-18} cm². This value is 300 times greater than the photoelectric cross section, which comes next in importance. As a result the effect can be observed even when Fe^{57} is only a minor constituent of the absorber.

Why Is It Significant?

The practical importance of the Mössbauer effect is that when one eliminates recoil-energy losses, one removes the major cause of line broadening. In the absence of other causes of broadening the zero-phonon gamma ray exhibits a line width that depends only on the natural width of the excited state, which in turn is related to the lifetime of the state through the uncertainty principle. More precisely, this width is equal to $h/4\pi\tau$, where h is Planck's constant and τ is the mean life of the state. Since scattering experiments necessarily involve a source and an absorber, the observed line width will be twice as great; contributions of source and absorber add.

The resonant absorption that exists when source and absorber are at rest can be destroyed by moving one with respect to the other at a velocity sufficient to produce a first-order Doppler shift greater than the line width. For Fe^{57} a Doppler velocity of 10^{-2} cm/sec, the speed of the tip of the minute hand of an ordinary alarm clock, is enough to destroy the resonance almost completely. The Doppler shift ΔE for a velocity v and a gamma ray of energy E is given by

$$\Delta E/E = v/c \qquad (3)$$

This first-order Doppler *shift* should be distinguished from the Doppler *broadening* of the line. In a solid, Doppler broadening does not occur since the period of lattice vibrations is short compared with the nuclear transition times involved. A second-order Doppler *shift* due to these vibrations has, however, been observed, and I will discuss it later.

Line-Width Measurement

The first experimental determination of natural line width by this method was made by Mössbauer with the equipment of Fig. 1. A radioactive source on a turntable produces the gamma rays of Ir^{191m}, and the relative speed of source and absorber is proportional to the angular velocity of the turntable. Half-life of the Ir^{191m} state is $\sim 10^{-10}$ sec, and the natural line width, 4×10^{-6} ev. A Doppler velocity of only 10 cm/sec is enough to destroy the resonance absorption, and by observing the counting rate as a function of velocity the complete shape of the absorption line was mapped point by point (Fig. 2).

The line widths obtained in this way, both by Mössbauer and by other workers who repeated his experiments (*9, 10*), usually proved to be greater by as much as a factor of two than those computed from the directly measured lifetimes. This broadening is believed to arise from inhomogeneous quadruploe and hyperfine interactions. Recent investigations using Fe^{57} have proved that it is possible, by preparing the source with extreme care, to reduce such interactions enough that natural line widths can be directly observed (*11*).

Although Mössbauer's original work was done with Ir^{191}, more recent workers have found that Fe^{57} is even more useful for many applications (*12*). Since the energy of the gamma ray emitted by Fe^{57} is small (14.4 kev) and the lattice vibration energy is large, the fraction of zero-phonon processes is large; in fact, the Mössbauer effect in Fe^{57} is the largest known. In addition, the line width is about as narrow as can be conveniently used: the line width is inversely proportional to the lifetime of the excited state ($\sim 10^{-7}$ sec for Fe^{57}), and the use of nuclides with greater lifetimes leads to considerable experimental difficulties. A good Mössbauer nuclide should also have a small conversion coefficient and a parent nucleus with a half-life of at least a few days (see table). Although Fe^{57} is not an extreme example of any of these properties, it does represent a successful compromise.

Second-Order Doppler Shift

In the course of the gravitational experiments described in the box on this page it was found that the gravitational shift is not the only effect to create a shift in energy between emission and absorption lines. A displacement of comparable magnitude arises from the second-order Doppler effect due to thermal motion of the

A Dramatic Example: The Gravitational Red Shift

One of the first problems to be tackled with the Mössbauer effect in Fe^{57} was measurement of the gravitational red shift; that is, the change in energy of a photon as it travels between regions of different gravitational potential. The magnitude of the effect can be derived by imagining a photon of energy E and effective mass m ($=E/c^2$) moving in a gravitational field g. If it drops a distance h it will gain an energy $mgh = Egh/c^2 = \Delta E$, which gives

$$\frac{\Delta E}{E} = \frac{gh}{c^2} = 1.1 \times 10^{-16}\, h \qquad (4)$$

(h is expressed in meters). Since the Mössbauer line width of Fe^{57} is 4.6×10^{-9} ev and the gamma-ray energy is 14.4 kev, it occurred to a number of workers (13, 14) that the resulting fractional line width of 3.2×10^{-13} might be small enough to allow the measurement of the red shift over distances available in the laboratory. Zn^{67} was also proposed (13, 15). Existence of the expected effect has been demonstrated (16) and verified (17) to within 5%.

The red shift in an accelerated system has been demonstrated by a group at Harwell using a high-speed rotor with a source of Fe^{57} deposited near the center and an absorber of metallic iron located on the periphery (18). Potential $\omega(R_1^2 - R_2^2)/2$ rather than the gravitational potential gh, and the pertinent equation can be derived in an analogous way.

The observed effect is in excellent agreement with the prediction. The presence of this red shift in an accelerational as well as in a gravitational field can be considered to be a verification, for photons, of Einstein's principle of equivalence, which states that no distinction between these two types of field can be observed in any physical experiment.

atoms (*19*, *20*); in a metallic iron foil a difference in temperature as small as 1° C can shift the energy as much as a 20-meter difference in height. The energy shift is proportional to the mean-square velocity of the atoms; that is, to their kinetic energy; and the fractional shift is given by the ratio of the kinetic energy to Mc^2

$$\frac{\Delta E}{E} = -\frac{1}{2Mc^2}\int C_L dT \qquad (4)$$

(C_L is lattice specific heat; M is mass of an atom). Near room temperature this amounts to a fractional shift of 2.2×10^{-15}/° C in iron. Other shifts of comparable magnitudes, probably due to differences in the exact chemical constitution of sources and absorbers, have also been observed (*19*).

Nuclear Spectroscopy

The fact that line widths obtainable with the Mössbauer effect are close to natural line widths, which makes possible the relativistic measurements just described, also suggests a number of applications in the field of nuclear spectroscopy. Since the line width in Fe^{57} is smaller than a representative value for the nuclear hyperfine interaction, it should be possible to resolve the hyperfine structure of iron in a line width type experiment (*12*, *21*, *22*).

When source and absorber are of the same material, the splitting is the same in both, and when they are mutually at rest there will be an absorption line for every emission line, resulting in a total absorption indistinguishable except for intensity from that of an unsplit line. The absorption measured as a function of Doppler velocity will then exhibit a strong line centered on zero velocity and a number of weaker lines at those velocities which again bring an emission line into coincidence with an absorption line. A typical result of this sort obtained by the group at the Argonne National Laboratory (*22*) is shown in Fig. 3, together with the hyperfine spectrum deduced from it. Here the ground-state moment and spin were known, so that the moment and spin of the excited state, as well as the hyperfine field at the iron nucleus, could be determined. The direction of the local field with respect to external magnetization has also been determined (*23*).

A considerably simpler absorption spectrum is obtained if either source or absorber contains iron in a state

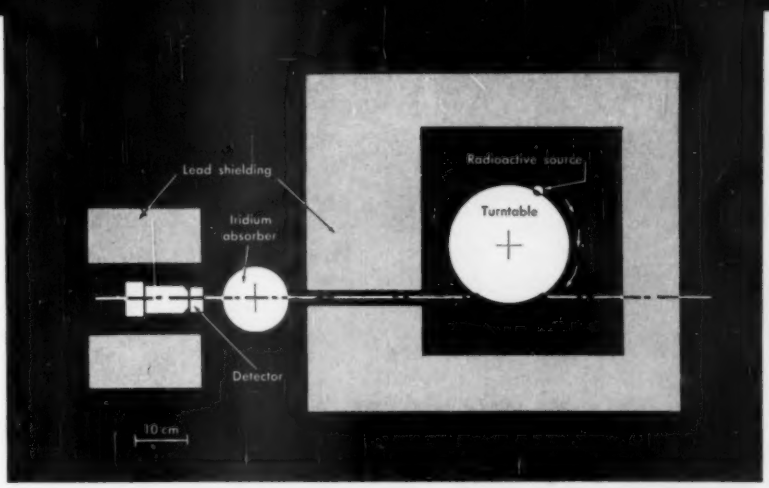


FIG. 1. NATURAL-LINE-WIDTH MEASUREMENT uses Os^{191} source on turntable, scintillation detector and iridium absorber between. Os^{191} decays to Ir^{191m}, and absorption of Ir^{191m} gamma photons depends on speed (see next figure)

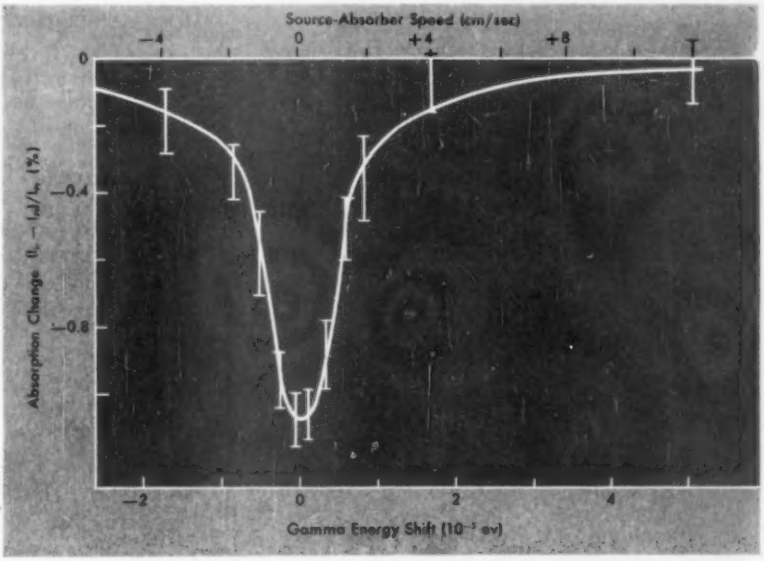


FIG. 2. ABSORPTION DIFFERENCE as function of speed shows line width. With equipment of Fig. 1, Mössbauer compared intensity of Ir^{191m} gammas through iridium and platinum absorbers

Nuclides That Have Shown Mössbauer Effect

Stable nucleus	*Parent nucleus*	*Parent half-life*	$E\gamma$ (*kev*)	*Excited-state half-life* (*sec*)
Fe^{57}	Co^{57}	270d	14.4	1.0×10^{-7}
Zn^{67}	Ga^{67}	80h	93	9.3×10^{-6}
Sn^{119}	isomer	250d	24	1.9×10^{-8}
Dy^{161}	Tb^{161}	6.88d	26	2.7×10^{-8}
Er^{166}	Ho^{166}	27.3h	81	1.7×10^{-9}
Tm^{169}	Yb^{169}	31.8d	8	?
Hf^{177}	Lu^{177}	6.75d	113	?
Ta^{181}	W^{181}	145d	136	5.7×10^{-11}
W^{182}	Ta^{182}	115.1d	100	1.3×10^{-9}
Re^{187}	W^{187}	24.0h	134	?
Ir^{191}	Os^{191}	16.0d	129	1×10^{-10}
Ir^{193}	Os^{193}	30.6h	73	5.7×10^{-9}
Tl^{197}	Hg^{197}	65h	77	1.9×10^{-9}

that is not split into sublevels by a magnetic field. Under these conditions the absorption measured as a function of Doppler velocity exhibits the hyperfine spectrum directly. Iron has this property when it is in stainless steel, potassium ferrocyanide (*24*), or sodium ferrocyanide (*25*). Figure 4 shows the hyperfine spectrum of Fe^{57} in a metallic iron absorber, obtained with a stainless-steel source; with such a source, the hyperfine splittings in other ferromagnetic or antiferromagnetic materials can also be obtained. The measured values of these splittings, together with the known nuclear moments, allow determination of the local fields in these materials, which are of great interest to solid-state physicists. In an experiment using an unsplit source and Fe_2O_3 absorber, Kistner and Sunyar found evidence for quadrupole splitting in addition to hyperfine splitting (*26*). Iron-bearing materials are not the only ones that can be investigated by this method. Local fields at impurity iron atoms in metals (*24*) and other substances have also been measured.

Further Experiments

A number of other experiments made possible by the high resolution obtainable with the Mössbauer effect have been proposed and some have already been carried out. In principle, it should be possible to detect the anisotropy of inertia with respect to the galactic center since such an anisotropy leads to small differences in the energy of hyperfine components of nuclear gamma rays depending on orientation of the nuclei in space (*27*). The effect, if observed, would be evidence that the accelerational mass depends on the distribution of matter in the universe; that is, that it is a tensor rather than a scalar. The resulting directional dependence of mass would manifest itself in the kinetic energy of any particle. In a nucleus it would produce differences in energy levels depending on differing orientations of nucleon orbits. A recent experiment with Fe^{57} failed to detect such an effect but made it possible to place a new upper limit of 5×10^{-16} on the magnitude of the anisotropy (*28*).

Recoilless Rayleigh scattering of nuclear gamma rays by electrons in solids has also been demonstrated with the Mössbauer effect in Sn^{119}. In this experiment the gamma rays reach the absorber only after being scattered (absorbed and re-emitted) by an intermediate scatterer, which may be any material *not* containing the resonant nuclide. In a sense this technique extends the scope of the Mössbauer effect to the study of all solids, even those into which suitable nuclides cannot be incorporated.

Scattering experiments in which the detector sees only gamma photons that have been absorbed and re-emitted by the scatterer can also be done with the resonant nuclide. Such experiments have a number of drawbacks when compared to the simple transmission experiment. In particular, geometric considerations and the large internal-conversion coefficients of most Mössbauer nuclides make it necessary to use very much stronger sources, giving rise to serious background problems. Such an experiment performed with Sn^{119} has been reported, however (*30*). Finally, it has been proposed that the coherent nuclear scattering of gamma rays (nuclear Bragg scattering) may be detectable with the Mössbauer effect (*31*).

Another problem that has received a definitive answer is whether the width of a nuclear level changes within a time after the creation of the state equal to the mean life of the state. The uncertainty principle suggests that if only those gamma rays emitted within a time much shorter than the first mean life were to be observed, the resulting line would appear significantly broadened. An equivalent experiment, one that has actually been performed, examines the magnitude of the nuclear-resonance absorption as a function of the time elapsed after the creation of the excited state (*32*). It was found that the absorption is small immediately after the formation of the state, indicating a broad line, and then approaches the normal value at times large compared with the mean life.

So far we have confined our discussion almost exclusively to the nuclides Ir^{191}, originally used by Mössbauer, and Fe^{57}, which has been most widely used in subsequent investigations. Successful experiments have also been performed, however, with a number of other nuclides (see table). Barloutaud and his colleagues have measured the line width in Sn^{119}, which has a gamma energy of 24 kev and a half-life of 1.9×10^{-8} sec (*33*). This nuclide is of particular interest because the pertinent gamma ray is part of a gamma cascade from the long-lived

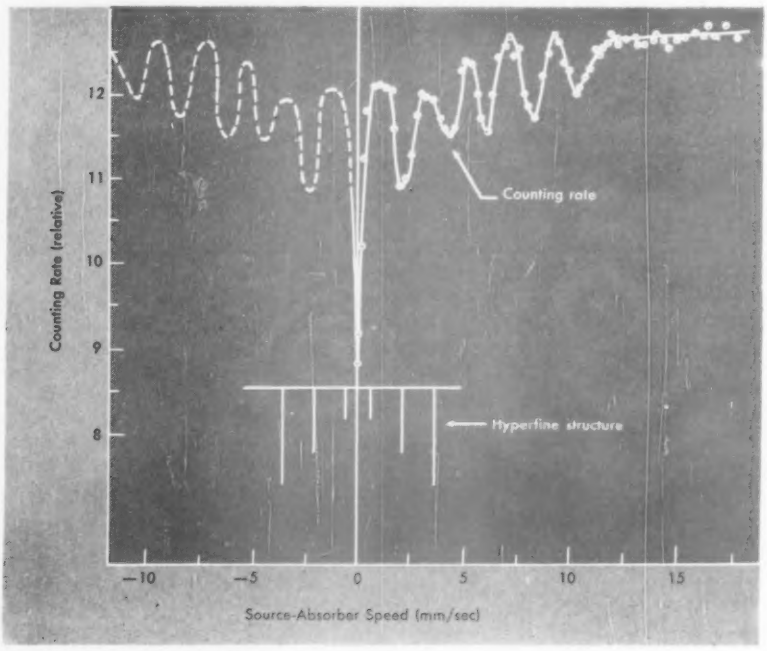


FIG. 3. HYPERFINE-STRUCTURE superposition with Fe^{57} in both source and absorber is revealed by counting-rate changes

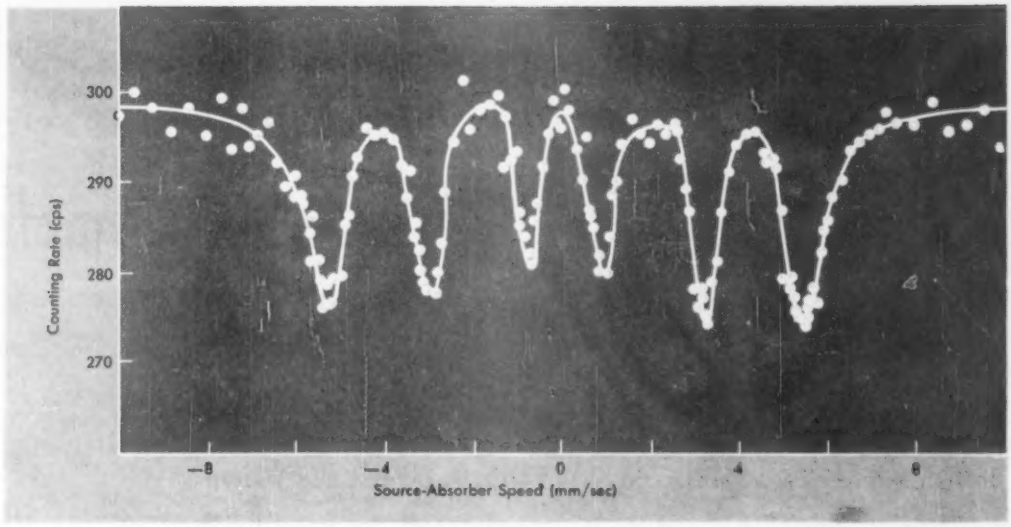


FIG. 4. UNSPLIT Fe^{57} LEVEL in stainless-steel source permits hyperfine structure in iron absorber to show directly

isomer of Sn^{119}; there is no preceding beta or electron-capture decay that might disturb the environment of the atom. The group at the Los Alamos National Laboratory has demonstrated the effect for Au^{197} (*34*), with a gamma energy of 77 kev and a lifetime for the first excited state of 1.9×10^{-9} sec. Zn^{67} has aroused considerable interest (*13, 35–37*) because it has the longest lifetime of any suitable nuclide found so far, but the relatively large energy (93 kev) and low Debye temperature of metallic zinc require liquid-helium temperatures for both the source and the absorber. To date an effect of less than ½% absorption has been obtained, but no measure of the line width has been given. Mössbauer has recently reported the observation of the effect in Re^{187} (*38*), and the Argonne group has observed it in W^{182} (*12*). The use of isotopes of silver with half-lives of the order of a minute has also been proposed (*39*), but there is no expectation that the corresponding natural line widths can be approached experimentally.

In Other Fields

The Mössbauer effect, although a product of nuclear physics, promises to have its greatest impact in other fields, particularly solid-state physics. In nuclear physics the effect can be used to determine spins and moments of first excited states of a limited number of nuclei. Its ability to determine natural line width is in part vitiated by discovery that measured line widths are usually broadened by extranuclear effects. It is precisely these effects, however, that promise to be of interest in solid-state physics. Thus Fe^{57} has already served to determine local fields in various ferromagnetic and antiferromagnetic substances. There is a real possibility that binding of impurity atoms and existence of localized vibrational modes will be demonstrated. There is even some hope that single-phonon Mössbauer lines can be resolved, making this effect a tool for the study of the phonon spectrum.

This by-no-means-complete list suggests that the Mössbauer effect will hold the interest of solid-state physicists for some years to come, long after its nuclear-physics possibilities have been exhausted. In this respect it is reminiscent of, though perhaps more promising than, two other phenomena which also bridge the gap between nuclear and solid-state physics: angular correlation of successive nuclear radiations and positron annihilation in solids.

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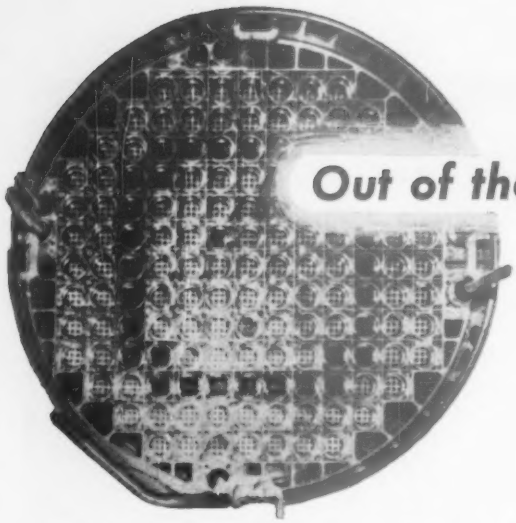

Out of the Shippingport Core...

Zircaloy Cladding

By B. LUSTMAN, M. L. BLEIBERG, E. S. BYRON, J. N.

Bettis Atomic Power Laboratory, Westinghouse Electric

Bettis experience with Zircaloy-clad UO_2 fuel rods has shown

1. **Zircaloy-cladding integrity is not adversely affected by 6×10^{21} nvt (fast)**
2. **Corrosion failure by hydriding can be avoided or kept to an acceptable level**
3. **Commercial vendors can produce acceptable Zircaloy-2 cladding with a 45% yield**

THE RECENT REPLACEMENT of the first seed elements in the Shippingport PWR afforded the opportunity to remove some of the more highly exposed Zircaloy-2-clad, natural-UO_2 blanket elements for destructive examination. This examination plus operation and fabrication experience have increased confidence in zirconium-base alloys as cladding for UO_2-rod elements. The conclusions are:

1. Zircaloy-2 cladding performed satisfactorily after a peak burnup of about 9,000 Mwd/ton UO_2, a general examination of the blanket elements showed. A detailed metallurgical examination of some twenty of the more highly exposed of these elements is now underway. One of these had operated for 5,800 equivalent full-power hours in 545° F water to an average UO_2 burnup of 5,500 Mwd/ton with a peak heat flux of 460,000 Btu/hr/ft² and an integrated fast flux of 5.8×10^{21} nvt. Examination of this element showed no dimensional, microstructural or corrosion evidence of radiation damage or loss of cladding integrity.

2. The yield of acceptable tubing from a commercial vendor was 45% at the end of the Shippingport fabrication effort. It was attained in the face of the many factors (chiefly ease of contamination and relatively low ductility) which make Zircaloy-2 more difficult to fabricate than more common materials. A 45% yield from ingot to finished mill product compared quite favorably with yields encountered with more common Zircaloy mill products or in the fabrication of conventional metals to as exacting specifications.

3. Radiation exposure of Zircaloy-2 in 475° F water to $5.5–6.0 \times 10^{21}$ nvt (fast) results in a marked elevation of yield and tensile strengths characteristic of fast-neutron exposure of structural metals. However, useful

Perspective on Zircaloy Cladding

The status of Zircaloy fuel cladding for civilian power reactors is clouded by the following seemingly contradictory evidence: (a) the successful Shippingport experience told in the accompanying article; (b) General Electric's original trouble with the Dresden first-core Zircaloy cladding and its consideration of stainless for the second core and for the SENN reactor; (c) the Canadian adoption of Zircaloy.

First, Shippingport does not provide the final answer. More advanced power plants will require higher thermal output, longer fuel life and, for natural-U reactors, thinner cladding for neutron economy.

Zircaloy components are now of better quality than those available during Shippingport production. Use of vacuum-melted stock has eliminated the stringers previously present, and tubing now made is free of fine cracks (~0.001 in. deep) that were common earlier.

Production of Dresden fuel was troubled by internal cladding cracks. Modified fabrication and testing overcame this prior to reactor operation. The first-core fuel is performing satisfactorily.

Apparently behind GE's serious consideration of stainless is concern about the basic properties of Zircaloy. Its corrosion and hydriding resistance decrease with increasing temperature. Therefore, the higher thermal output desired for the Dresden second core and future reactors may lead to the choice of stainless in the absence of proven (to GE) Zircaloy data.

Another kind of unknown is whether fluoride in the UO_2 played a part in the failure of Dresden prototype fuel tested in VBWR in 1959. This might be a problem with enriched fuel, such as that in Dresden, because of the extra UF_6 enrichment step. GE and Chalk River are exploring this.

The concensus of all parties seems to be that Zircaloy has a place in water reactors. But to clarify the hazy perspective more development and testing are needed.

—THE EDITORS

Performs Well in PWR

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ductility decreased only slightly in tensile tests of notched and unnotched specimens, fatigue-limit tests or notch-impact tests.

4. Local hydriding of cladding aggravated failure of intentionally defected Zircaloy-2-clad UO_2 elements in in-pile hot-water loop tests. Only defected elements, however, have failed in this way. Tests show that elimination of nickel, one of the constituents (0.05%) of Zircaloy-2, delays or prevents such failures. Zircaloy-4 (<0.007% Ni) behaves better in this respect.

5. The only other type of failure encountered during tests of these elements has been "waterlogging" (water permeating the interior of the fuel element through a small cladding defect flashes to steam, causing high internal pressures), which is characteristic of unbonded fuel elements and can occur with any cladding material.

Performance of Fuel in PWR

Fission-product activity in the coolant after 5,800 hr of full-power operation of the first seed and blanket and after return to full power with the second seed indicates no more defected fuel rods than probably were present at the start of core operation.

The defected-fuel-rod fission-product-activity release has been estimated to be equivalent to 0.61 kw. This is about one-half the average output of one of the 95,000 fuel rods in the reactor blanket, which operates at 120 Mw(th) (*1*). This estimate is based on loop tests that showed that, during steady-state operation, the rate of fission-product-activity release from a cladding defect of given size is proportional to fuel-element power production. Thus it can be concluded that few defected elements are in PWR blanket.

We are examining metallurgically one of the more highly exposed 120-rod blanket bundles removed at the end of Seed 1 life (*2*). Preliminary results on one of these rods (burnup, 5,500 Mwd/ton of UO_2; cladding integrated fast flux, 5.8×10^{21} nvt) showed no significant changes in cladding dimensions, microstructure or hydrogen content.

We plan to pressure-test the cladding in this bundle; the internal pressure required to burst the cladding is an over-all measure of cladding strength. In pressure-burst tests on a bundle [WAPD-30-2 test (*3*)] exposed in a high-temperature (540° F) water loop in the MTR for about 200 days to an integrated fast flux of 1.3×10^{21} nvt (Table 1), only one rod (number 9) showed a substantially low bursting strength—and it lies within the variation anticipated for this highly sensitive test. These test results corroborate Shippingport experience to date: cladding integrity has suffered no reduction due to irradiation embrittlement or to loss in ductility caused by hydrogen absorption.

Zircaloy-2 Tubing Quality

The bulk of the Zircaloy-2 seamless tubing used in the blanket of the Shippingport reactor was fabricated by one commercial tubing vendor.

In setting up fabrication and inspection procedures (*4, 5*), it was necessary to account for those properties unique to zirconium-base alloys. For example, the galling tendencies of zirconium alloys require a jacket during extrusion

TABLE 1—PWR Rod-Bundle Tests*

Rod No.	*Bursting pressure (psi)*	*ppm hydrogen*
1	13,000	84
3	12,500	
5	9,500	57
6	12,500	
9	6,000	73
11	13,000	45
12†	9,000	
14†	8,000	
16†	9,000	
Unirradiated	9,500–14,000	

* All rods 1–16 exposed to 1.3×10^{21} nvt.
† These rods damaged during remote machining from irradiated bundle.

TABLE 2—Processing Yields of PWR Zircaloy Tubes

Process	*Yield (%)*
Sponge to conditioned ingot	92
Conditioned ingot to extruded bar	90
Extruded bar to machined billets	74.4
Machined billets to conditioned tube shell	86
Conditioned tube shell to vendor acceptable mill length (includes processing loss and vendor inspections loss, based on 50,000 lb of ingot material processed)	71
Over-all yield by processor (items 1 through 5)	37.6
Vendor acceptable mill length to consumer acceptable mill length (based on 7,000 lb ingot processed and eddy-current inspection)	99.87
Vendor acceptable mill length to consumer acceptable mill length (based on 7,000 lb ingot processed and dimensionally inspected)	99.68
Vendor acceptable mill length to consumer acceptable fuel-rod-tubing lengths (based on 50,000 lb ingot processed and all inspection rejections)	98

to allow proper material flow. To prevent inclusion of compounds of the jacketing material and zirconium in the tubing surface (thus leading to mechanical defects or corrosion-sensitive sites), Superior Tube conditioned the extrusions by machining or pickling. Shear cracks have formed in Zircaloy-2 at cold reductions greater than 40% in cold-compression tests. Thus, working and annealing schedules were adjusted to avoid formation of even tiny cracks if they could not be healed in subsequent operations. Proper vacuum practice during annealing operations prevented absorption of nonmetallic gaseous impurities, which reduce ductility or corrosion resistance.

Table 2 lists the fabrication yields attained for Shippingport tubing. These acceptance rates reflect Bettis inspection of 15–20-ft lengths used in the blanket fuel elements. Thus the yield information should be applicable to tubing for longer-length fuel elements.

An important factor in current Zircaloy-fabrication practice that contributes to a higher-quality product is the use of vacuum melting. The Zircaloy used in Shippingport, on the other hand, was fabricated from inert-atmosphere-melted ingots and contains inert-gas inclusions, which can lead to "stringers" (*6*) and consequent impairment of ductility, integrity and corrosion resistance.

The data in Table 2 indicate that, of the 50,000 lb of ingot processed to tubing for Shippingport, the over-all yield (item 6) of product meeting the specifications supplied to the vendor was 38%. This is comparable to yields obtained for other Zircaloy mill products supplied to reactor-grade specifications. In fact, toward the end of this particular effort improvement in the vendor's processes had increased his yield to about 45%. The over-all yield of tubing lengths acceptable for use in the Shippingport plant, for the 50,000 lb processed, was about 98% of that supplied by the vendor (item 9). During the later stages of production by Bettis, the rejection rate of tubing supplied by the vendor was so small (items 7 and 8) that the tubing was finally supplied already cut to fuel-rod lengths and was inspected by Bettis on a 10% sampling basis (refs. *6* and *7* describe Bettis inspection techniques.)

TABLE 3—Tensile Properties of Irradiated Zircaloy-2*

Condition	*Test temp. (°F)*	*0.2% offset yield strength (psi)*	*Ultimate tensile strength (psi)*	*% total elong.*	*% red. in area*	*% uniform elong.*
Nonirradiated						
Unnotched	R.T.	43,000	69,400	32.9	44.3	17.9
Unnotched	600	22,350	34,600	35.4	59.9	11.7
Notched	R.T.	52,300	72,200		13.4	
Notched	600	24,900	38,400		44.2	
Irradiated (5.5–6.0 × 10^{21} nvt)						
1st series						
Unnotched	R.T.	93,800	95,900	10.1	27.5	1.3
Unnotched	600	73,200	73,200	12.6	38.4	0.0
2nd series						
Unnotched	R.T.	94,200	94,800	8.6	28.3	1.2
Unnotched	600	57,650	57,700	13.4	55.0	0.2
Notched	R.T.	105,500	106,200		4.6	
Notched	600	60,000	60,000		29.2	

* Exposure was 5.5–6.0 × 10^{21} nvt (fast) in 460° F water.

Radiation Damage

Fast-neutron damage to the tensile properties of Zircaloy is manifested, as for almost all structural and cladding metals, by an elevation of yield strength, a somewhat smaller increase in maximum tensile strength and a reduction in elongation of gage length of the tensile specimen at fracture.

The change in properties of Zircaloy-2 upon irradiation almost reaches saturation at exposures of 1 × 10^{21} $n_f$vt (Fig. 1). Cladding integrity is most likely to be impaired by reduced ductility as measured by total elongation. However, the latter is a complex quantity affected not only by material properties but also by test-specimen configuration; it is composed of uniform elongation, i.e., the amount of plastic strain between the yield and maximum tensile strength, which is a measure of the strain-hardening rate of the mate-

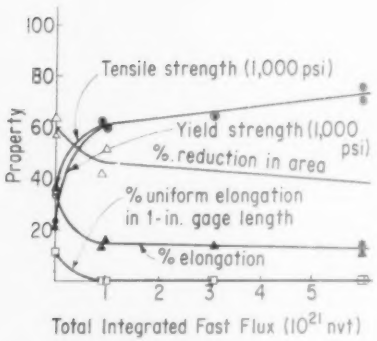

FIG. 1. FAST-FLUX EFFECT on 600° F tensile properties of Zircaloy-2

TABLE 4—Fatigue Properties of Zircaloy-2

	Nonirradiated		*Irradiated (~5.0 × 10^{21} nvt)*	
	Unnotched	*Notched, K_T = 3**	*Unnotched*	*Notched, K_T = 3**
Failure stress at 10^6 Cycles (psi)	24,000	15,500	21,500	13,000
K_t†		1.55		1.60
q‡		0.275		0.30

* K_T = theoretical stress-concentration factor.

† $K_t = \frac{\text{stress unnotched}}{\text{stress notched}}$ = strength-reduction factor.

‡ $q = \frac{K_t - 1}{K_T - 1}$ = notch-sensitivity factor; q = 1 for completely notch-sensitive material.

rial, and the localized deformation or necking occurring prior to fracture. Uniform elongation is sharply reduced in structural materials by fast-neutron exposure.

In most fuel-element designs, the cladding is selected to operate at or below a nominal stress corresponding to the yield strength of the material. Therefore, the most significant mechanical-property index of cladding integrity is that which predicts the ability of the material to withstand localized high stresses caused by cracks formed during fabrication or notches introduced during fuel-element assembly. The reduction in area in a tensile test, particularly in prenotched specimens, is considered the best measure of this stress behavior.

Data from mechanical-properties tests of Zircaloy-2 irradiated at room temperature and at operating cladding temperature (Table 3) clearly show the expected increase in strength with accompanying loss in ductility. Some specimens were prenotched to give a theoretical stress-concentration factor of about 4. Behavior is similar, but with smaller changes in properties at lower fast-neutron exposures (*8–10*).

The decreased total elongation in the unnotched specimens, as indicated earlier, primarily results from the increase of the yield strength almost to the value of the ultimate tensile strength. The ductility that remains appears as localized plastic deformation, which is not clearly reflected in the total-elongation values but appears as an appreciable reduction in area prior to fracture. Irradiation has little effect on ductility, as reduction-in-area values show in Table 3 and Fig. 1. Thus, it is inferred that, in terms of the behavior of Zircaloy-2 cladding or structural components, sufficient ductility remains after irradiation to relieve large strains caused by fuel swelling, thermal stresses, etc. Also, brittle-type failures will not occur even at stresses far above the design stresses, which nominally are below the nonirradiated yield strength.

The notched tensile tests in Table 3 further confirm the ductile behavior of irradiated Zircaloy-2. First, both irradiated and nonirradiated Zircaloy-2 show a slight notch-strengthening effect indicative of the ability of the material to relieve high local stresses at the notch; the magnitude of the strengthening is unaffected by irradiation. Secondly the reduction-in-area values, particularly at operating temperatures, illustrate a large amount of ductility remaining after irradiation even in prenotched samples. Thus brittle behavior induced by areas of high stress concentration (at least up to a factor of 4) is not expected in Zircaloy-2 irradiated to 6×10^{21} nvt or, by extrapolation from lower exposure

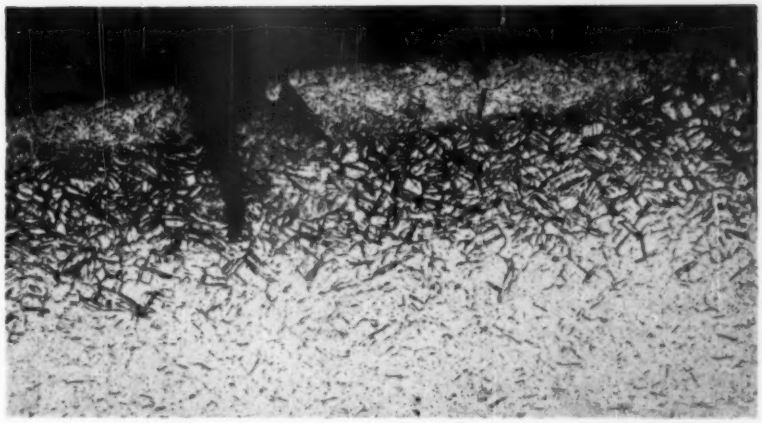

FIG. 3. LOCAL HYDRIDING on test element. Photomicrograph (100X) shows segregation of hydriding at outer cooled surface of cladding and crack extending through hydrided region. Other sections of element indicate that crack extends through cladding

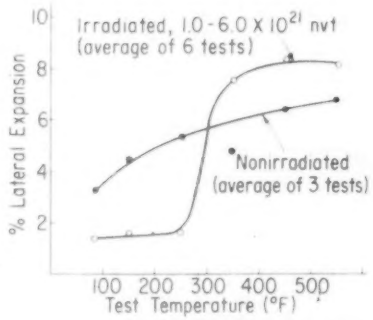

FIG. 2. NOTCHED IMPACT TESTS show useful ductility of irradiated Zircaloy-2 at temperatures over 250° F

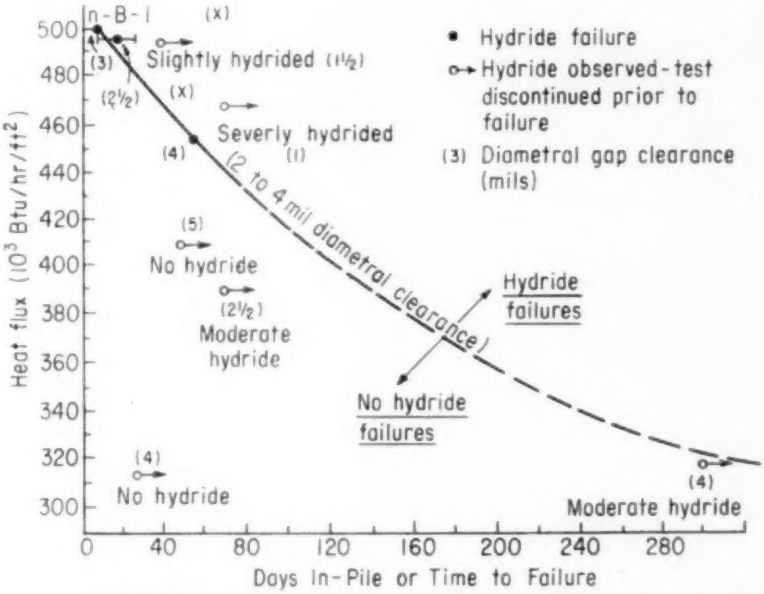

FIG. 4. HYDRIDING of Zircaloy-2 in defected Shippingport Core 1 blanket fuel-rod samples in in-pile, high-temperature water loop. No hydride or failures observed in rods with 0.008-in-diametral clearance; these rods indicated by (x)

data, at much higher exposure levels.

The dynamic behavior of Zircaloy-2 (fatigue, impact, creep) after irradiation further illustrates the adequacy of Zircaloy-2 as a cladding material. Bending tests on notched and unnotched 0.100-in.-thick plates show only slightly reduced fatigue strength after 5.0×10^{21} nvt (Table 4). Furthermore, the strength-reduction factor and the notch sensitivity observed in the irradiated notched specimens (theoretical stress-concentration factor of 3) did not differ significantly from those of the nonirradiated specimens.

Recent notch-impact data obtained from material irradiated in the same series of tests show no deleterious effects on transition-type behavior or energy levels over nonirradiated material. This confirms earlier results (*11–13*) at lower fast-neutron exposures.

Another frequent measure of the resistance of metals to brittle fracture is the lateral strain parallel to the notch in square-notched impact specimens. Results of such measurements at a series of temperatures (Fig. 2) again confirm the existence of useful ductility in irradiated Zircaloy, particularly above 250° F. Preliminary results from postirradiation creep-rupture tests at 600° F on Zircaloy-2 irradiated to about 5×10^{21} nvt show that comparable creep rates and rupture times occur at stresses 15,000 psi higher than those for nonirradiated Zircaloy-2.

Hydriding of Cladding

Present experience indicates that corrosion behavior—particularly hydrogen absorption—will be the factor that most limits the reactor life of Zircaloy-2 cladding. Localized high hydrogen concentrations have caused embrittlement and cracking (*3*).

The successful operation of pressurized-water reactors employing Zircaloy-2 cladding, the extensive out-of-pile corrosion testing extending to over 2,000 days testing in 600° F water and the lack of any apparent irradiation effect on corrosion rate all indicate that oxide formation should not be a Zircaloy-2-cladding corrosion problem. However, hydrogen uptake by the cladding concomitant with the corrosion reaction is a potential limit to the useful life of Zircaloy-2. Few corrosion failures of Zircaloy-2-clad UO_2-rod fuel elements, such as that shown in Fig. 3, have occurred in in-pile loop tests (*3, 14, 15*). Analysis of the failures indicated that several conditions are necessary to initiate such failures: a cladding defect, small diametral clearance between oxide fuel pellets and cladding material, high external surface temperature and high heat flux.

Figure 4 summarizes observations on cladding hydriding (*3*). Note that failure by local excessive absorption of hydrogen is sensitive to heat flux and fuel-cladding clearance.

No firm explanation of these failures is available. However, results to date indicate the following mechanism: Upon insertion of the defected fuel rod into the loop, reactor coolant enters the cladding defect. When the reactor is raised to power, reaction of the water or steam within the element with the Zircaloy-2 cladding or the UO_2 enriches the steam in hydrogen. The hydrogen reacts with the Zircaloy-2 cladding at localized sites and, under the influence of a thermal gradient (*16*), concentrates at the external surface of the cladding where at sufficiently high concentrations it may cause cracks.

A recent irradiation test supported this mechanism. A 10.5-in.-long Zircaloy-2-clad fuel rod of PWR Core 1 dimensions was deliberately designed for rapid hydriding failure. An intentional 0.005-in.-diameter defect was located about over the center of the top UO_2 pellet, and the clad-fuel diametral clearance was 3 mils. The calculated surface heat flux at full reactor power was ~500,000 Btu/hr/ft², which was expected to be sufficient to ensure a "hydriding"-type failure. The surface temperature of the element was ~630° F. The Zircaloy-2-clad fuel rod (sample N-B-1 in Fig. 4) failed 3¼ days after reaching full reactor power, as evidenced by high loop activity. Examination of the cladding in the failed region, following an additional 27-day exposure to reactor conditions, revealed excessive local hydride formation and the loss of a ¼-in.-dia. segment of cladding at the center of the element.

Enhancement of the hydrogen-absorption rates of Zircaloy-2 can be demonstrated out-of-pile by exposing samples to corrosion in high-temperature water containing excess dissolved hydrogen. Figure 5 shows this effect as well as the insensitivity under the same conditions of Zircaloy-4, an alloy similar to Zircaloy-2 except that the nickel content has been reduced to the level of the nickel impurity in the original Zirconium sponge. This modification to the Zircaloy composition was prompted by the earlier observation (*17*) that the addition of 0.5% Ni to

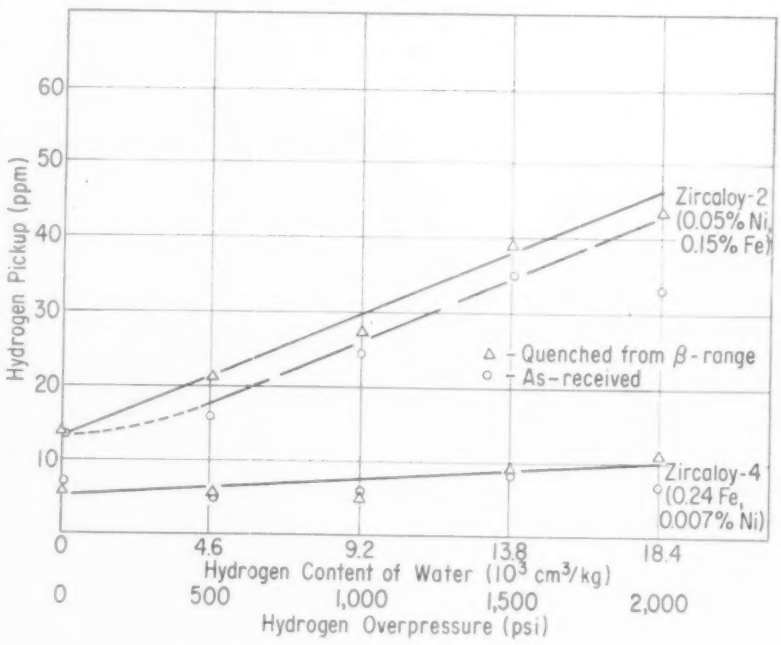

FIG. 5. HYDROGEN ABSORPTION by Zircaloy-2 and Zircaloy-4 during 2 weeks in 343° C water containing excess dissolved hydrogen. Low hydrogen pickup of Zircaloy-4 is attributed to low nickel content

Zircaloy-2 caused excessively rapid hydrogen absorption in-pile. This effect was also illustrated by the exposure of a fuel element sample in a test similar in all respects to sample N-B-1 of Fig. 4 except that the cladding material was Zircaloy-4 instead of Zircaloy-2. This sample survived the 40-day test period with no localized cladding deterioration in contrast to the failure of the Zircaloy-2-clad sample in 3¼ days.

Waterlogging Failures

Waterlogging is the only type of failure other than that caused by hydriding which has occurred in tests of Zircaloy-2-clad UO_2 rod-type elements.

In waterlogging (*3, 18*), water is trapped in the interior of a defected fuel element during reactor shutdown. As the fuel-element temperature increases rapidly during reactor startup, the steam formed cannot escape through the defect fast enough to relieve the internal pressure. Such failures generally occur only with low-density oxide fuel having large amounts of interconnected porosity. They are characterized by bulging of the cladding and longitudinal cracks similar to those observed in tubing-rupture tests under internal pressure. Thus, the conditions leading to these failures are the use of a fuel unbonded to cladding in water systems and the presence of a cladding defect. The nature of the cladding material is apparently less important in waterlogging than the characteristics of the fuel material and exposure conditions.

Figure 6 shows an intentionally defected test fuel rod that failed by waterlogging. The failure consists of a crack near the welded end cap of the fuel element. The fuel was only 80% dense and had been fabricated by hot pressing, as opposed to the cold pressing and sintering yielding 92–94% dense fuel which was finally used in the Shippingport reactor. After 43 days of operation of this fuel element in a high-temperature in-pile water loop, a burst of activity was noted during reactor startup. On removal of the specimen, the bulging and cracking were observed. Pressure tests to failure of unirradiated fuel elements show this same type of clad bulging near the end caps where welding has annealed the tubing and weakened the metal.

The only other indication of waterlogging failure in oxide rod elements was noted in a subsequent test of an intentionally defected fuel element; the fuel was cold-pressed and sintered to 90% density in a graphite muffle furnace. Contamination of the oxide by graphite during sintering caused corrodible carbide inclusions which, upon exposure to water, reacted and caused "desintering" of the oxide. Upon removal of the specimen after a 1-week in-pile irradiation, the cladding was more or less uniformly deformed about 2% on the diameter. This effect was attributed to waterlogging in the "desintered" oxide.

In the many samples of defected and nondefected oxide rod elements run since this period in which the oxide was fabricated to 92–94% density by cold pressing and sintering under well-controlled purity conditions, there was no further evidence of waterlogging. We thus feel that this failure mechanism is unimportant for the Shippingport-type fuel element.

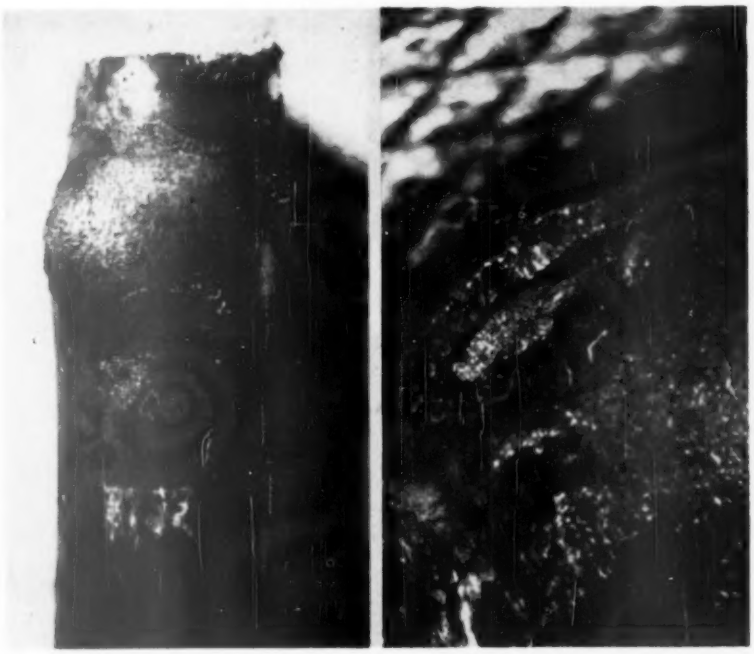

FIG. 6. WATERLOGGING FAILURE of defected oxide-rod fuel element. Photographs show bulge near welded end cap and associated crack

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Specific-Activity Nomogram

By T. ALEX EASTWOOD, *Atomic Energy of Canada Ltd., Chalk River, Ontario, Canada*

This nomogram gives values quickly for the specific activity (dps/gm) of a pure radionuclide, the total activity for a sample of certain weight or the weight required to give a particular total activity. By using it one can get answers to within ±20% of the correct value, and also check for arithmetical errors that may creep into computations.

The disintegration rate R for a weight W of a pure radionuclide of atomic weight A is given by the relation

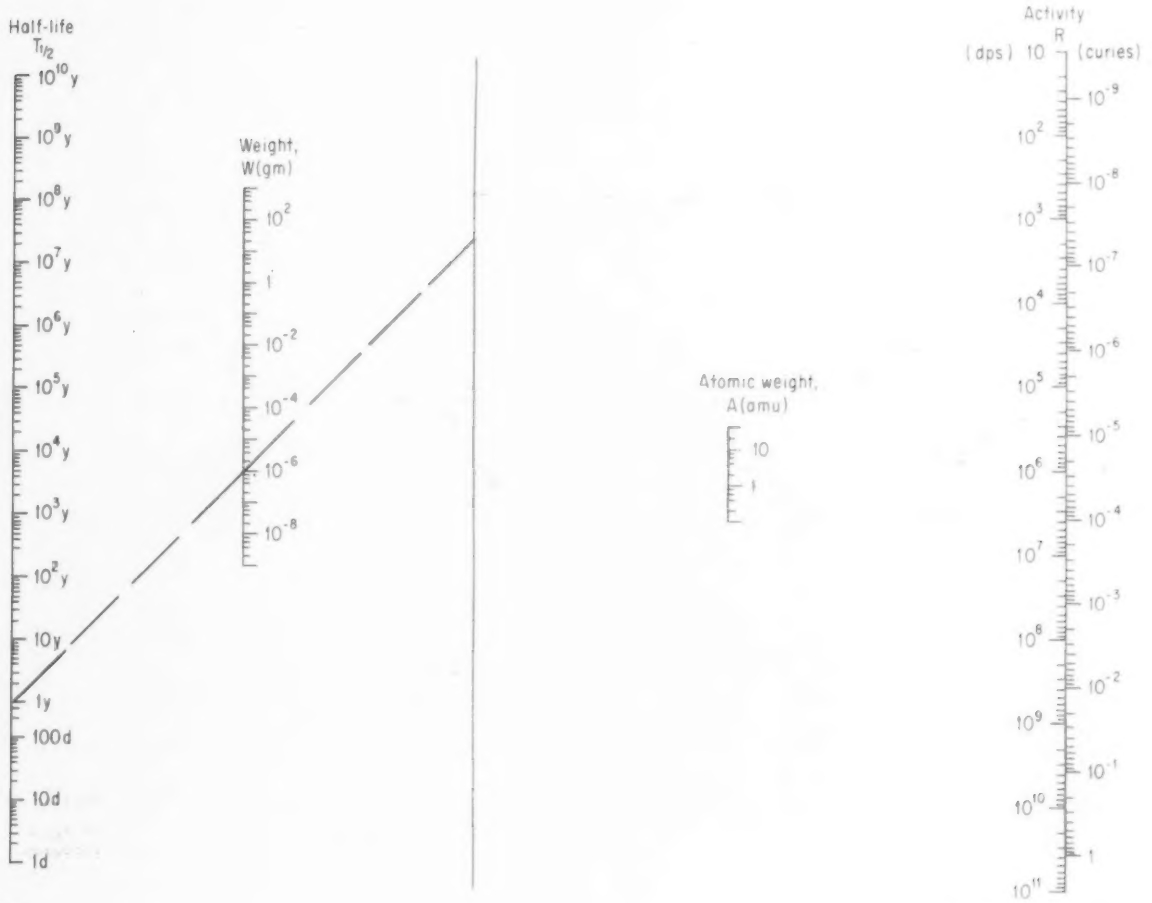
$$R = N_0\lambda = \frac{N_0 \times 0.693}{T_{1/2}}$$

$$= \frac{W}{A} \times 6.023 \times 10^{23} \times \frac{0.693}{T_{1/2}}$$

$$= \frac{W \times 4.17 \times 10^{23}}{A \times T_{1/2}}$$

when $T_{1/2}$, the half-life of the nuclide, and R are expressed in the same time units.

Example. To get the activity of 1 μg of Ru^{106} (1-year half-life) join 1 year on the $T_{1/2}$ scale with 10^{-6} gm on the W scale and project the line to the turning axis. A straight line joining the intercept on the turning axis and 106 amu on the A scale intercepts the R scale at 1.2×10^8 dps (3.3mc). Thus the specific activity of fission-product Ru^{106} is 1.2×10^8 dps/μg. (By reversing this procedure you can get the weight corresponding to a given disintegration rate.)



Trends in Sodium Equipment

Because most mechanical components for sodium reactors were adapted from designs for petroleum and water service, they fail to exploit sodium's superior heat-transfer ability and fall heir to thermal-stress problems. New designs alleviate these problems while fresh concepts forge the way toward 2,200-psi 1,050–1,200°F steam

By ROBERT W. DICKINSON and JOHN B. WILLIAMS
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LIQUID METALS are superior heat-transfer media for reactor systems, but development of reliable mechanical components has been a bottleneck. Experience shows that component problems are due mainly to a lack of appreciation by designers of the unique heat-transfer qualities of liquid metals. Current vigorous development of new sodium-reactor components is keeping liquid-metal-cooled reactors in the running for the goal of economic nuclear power. There are at least 17 sodium-cooled power reactors or experiments in existence or planned (*1*).

Seawolf and SRE Troubles

Operating limitations have had to be imposed on some sodium-cooled plants because of either outright component failure (as in Seawolf) or high-stress areas in components (as in SRE) where sodium temperature distributions turned out differently than we had

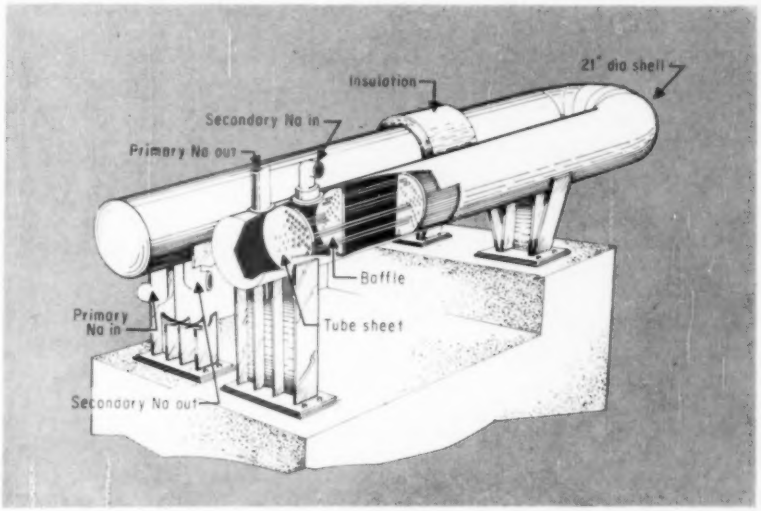

FIG. 1. FOR SRE intermediate heat exchanger we chose familiar shell-and-tube type mainly because of its seemingly routine design calculations and manufacturing familiarity. Although horizontal shell-and-tube configuration is popular for use with low-conductivity fluids such as water and petroleum, we have seen that shell-and-tube exchangers for Na service are more difficult to design structurally and thermally

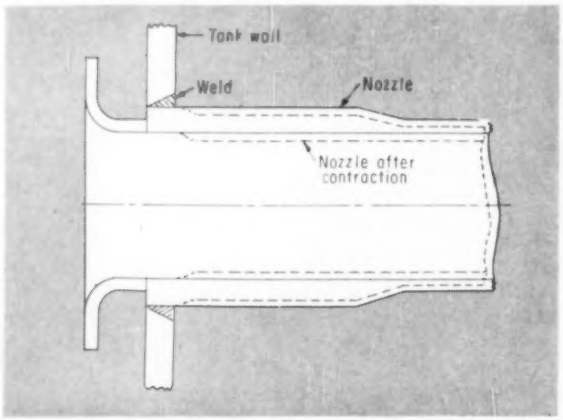

FIG. 2. SRE sodium-outlet nozzle on core tank tends to contract away from tank wall as shown when temperature of outlet sodium drops as it does when reactor is scrammed; heat storage capacity tends to hold tank-wall temperature steady, thus high stresses develop in the area of the function

FIG. 3. DISTORTION of thin shell of SRE Na-to-Na shell-and-tube heat exchanger around shell-to-sheet junction. When temperature of Na in tubes changed rapidly, temperature of thin tubes and thin shell followed quickly, but thicker tubesheet lagged, thermally stressing and bowing junctions and distorting shell

Chronology of Sodium-Cooled Reactors

1951—**EBR-1**, the 1.4-Mw(th) fast breeder at the National Reactor Testing Station in Idaho was not only the first reactor to produce electrical power but also the first to produce more fuel than it consumed. It has operated for nine years, produces about 200 kwe. Its simple concentric-nickel-tube heat exchanger would be costly if extrapolated to large power plants. NaK is pumped to the metallurgically bonded Ni tubes in the steam generator by d-c electromagnetic pumps. Component performance has been good.

1955—**S1G**, the prototype for the Seawolf intermediate-energy reactor, operated at West Milton, N. Y. until 1957.

1956—**S2G**, propelled the Seawolf 71,609 nautical miles. In 1959, because of steam-generator difficulties and heavier shielding requirements, along with the Navy's desire to standardize power plants, it was replaced by the S2WA pressurized-water reactor.

1957—**SRE**, which produces 20 Mw(th) for a system generating 6.2 Mwe at Santa Susana, California, has a U-shaped shell-and-tube Na:Na heat exchanger, a double-wall-tube once-through steam generator of all-stainless-steel construction (with Hg in the tube annulus) and freeze-seal mechanical pumps.

1959—**DFR**, a 60-Mw(th) fast reactor, has operated at Dounreay, Scotland, at low power with NaK coolant; plans are to switch to sodium later. It has E-M linear inductor pumps, a concentric NaK:NaK heat exchanger, and the tubes in the steam generator are bonded in a metal block.

1961—**EBR-2**, designed to operate at 62.5 Mw(th) and generate 21 Mwe, is being constructed at NRTS, Idaho. Its steam generator has separate ferretic tubes for sodium and for water; braze alloy between the duplex tubes separates the fluids and transfers heat. Na:Na heat exchange is via a shell-and-tube unit, while the pumps are d-c electromagnetic.

1961—**Fermi-1**, a 300-Mw(th) 90-Mwe fast breeder, is being built near Detroit. Its once-through steam generator has only single-wall tubes between the fluids. The Na:Na heat exchanger is of the shell-and-tube type; pumps are free-surface mechanical.

1963—**Hallam**, which will produce 240 Mw(th) for a system generating 76 Mwe in Nebraska, has free-surface mechanical pumps, a bayonet-type Croloy steam generator and a vertical shell-and-tube Na:Na heat exchanger with bellows in the shell.

Other liquid-metal cooled reactors include: Russia's experimental **BR-5**, which in 1958 generated 5 Mw(th) at Obninsk, and the planned **BR-5** and **BR-250** breeder reactors; Russia's **Volga** station sodium-graphite reactor, which will produce 50 Mwe at Ulyanovsk; France's **Rapsodie**, which will produce 10 Mw(th) at Cadarache in 1962; **LAMPRE-1**, whose molten plutonium fuel in 1961 will generate 1 Mw(th); Atomics International's **SNAP-2** (1959), **SNAP-8** and **SNAP-10** (1960) U^{235}-ZrH-fueled auxiliary-power reactors; **Fermi-2** (PFFBR or Plutonium Fueled Fast Breeder Reactor) is an advanced version of Fermi-1.

expected. In either case, there was little choice but to limit service conditions.

Seawolf. Probably the most widely heralded liquid-metal component casualty was the early failure of part of the steam-generating equipment in Seawolf (*2*). To avoid contact between boiler water and sodium in case of a leak, the shell-and-tube steam-generator design had been complicated by adding double tubes and double tubesheets; but this pressure-monitoring space between sodium and water sides made accurate stress analysis difficult. A corrosion-induced metal failure, and quite possibly an initial failure due to excessive stresses, caused the superheater to leak. Once the faulty superheater was bypassed the Seawolf system operated satisfactorily, although at reduced power.

SRE. We approached full-power operation of the Sodium Reactor Experiment cautiously, with the realization that our design stress analyses were only as good as our temperature-distribution assumptions. After we measured actual temperature distributions, analyses indicated no problems at steady full-power operation, but showed that post-scram temperature transients of 40° F/min could cause thermal stresses up to 40,000 psi (twice the yield strength at temperature) in the intermediate heat exchanger and core-tank nozzles shown in Figs. 1 and 2 (*3, 4*). Figure 3 shows how sudden sodium-temperature changes caused thermal stresses that distorted the shell of SRE's intermediate heat exchanger; Fig. 4 shows the pronounced temperature maldistribution due to stratification in the exchanger and Fig. 5 shows the effect of this laminar flow in unbaffled sections.

To prevent these excessive stresses we at first set a 10-Mw (half design power) operating limit on the reactor so as to keep the coolant outlet below 800° F. Later we installed eddy-current brakes (*4*) to limit post-scram sodium flow to keep temperature transients less than 30° F/hr. This kept stresses in the type-304 stainless steel below the yield point, permitting sustained operation at a full 20 Mw. Although we prevented stresses above the yield point in this critical area, use of eddy-current brakes would add about $300,000 to the cost of large systems.

Heat Exchangers

SRE experience has taught us ways to design better sodium heat exchangers. For instance, Fig. 6 shows the Hallam heat exchanger, which stands vertically to alleviate stratification and thermal stresses in the tubesheets and bellows in the shell expand as temperature changes (sodium-system components change temperature faster than water-system components because film coefficients in liquid metals are 3,000–10,000 Btu/hr/ft²/° F vs. only 500–2,000 for water). We also are studying other configurations and plan to test some large examples, perhaps including a shell-and-tube unit with fixed tubesheets and sine-wave tubes proposed by Alco (*6*). We have tested a 100-kw Graham "helicoil" heat exchanger; it maintained its mechanical integrity after steady runs at up to 1,200° F and transients up to 55° F/min.

Steam Generators

Development of corrosion-resistant materials and improved configurations promises improvements in steam generators such as that for the Hallam reactor shown in Fig. 7. Figure 8 shows a unique design we tested satisfactorily using SRE sodium. We also are considering testing various new concepts in our new sodium component test installation. Alco Products has proposed a design that features a bayonet-type evaporator, spherical steam

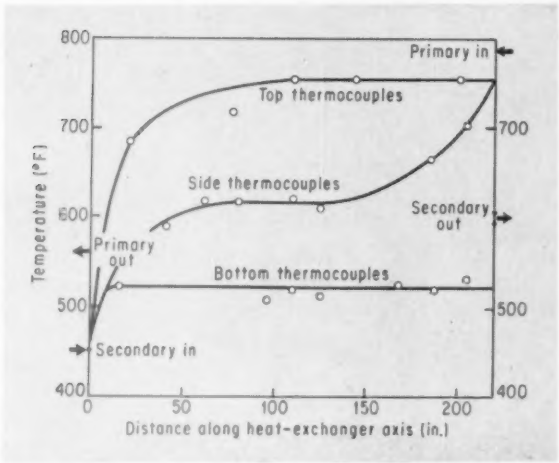

FIG. 4. TEMPERATURE DIFFERENCES between secondary Na flowing in top, middle, and bottom of SRE intermediate heat-exchanger shell 3 min after scram from 14 Mw ($\Delta T = 270°$ F) result from density stratification of horizontally flowing Na due to 200–500° F gradients (vs. 10–100° F common with water or oil). Both primary and secondary Na were flowing at 1,300 gpm

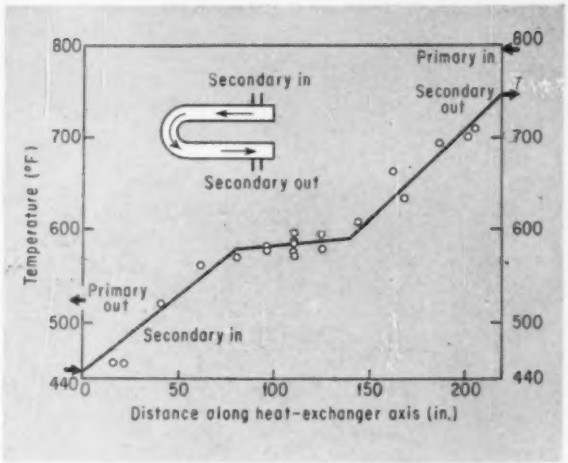

FIG. 5. NEARLY FLAT CENTER portion of Na-temperature plot in SRE heat exchanger (with reactor at steady 14 Mw) shows how heat transfer in unbaffled bend section suffers from laminar flow stratification (5). Strata setup difficult-to-calculate stresses in tube sheets, which are complicated further when reactor power level changes suddenly and changes temperature of flowing sodium

drum and shell-and-tube superheater (6), while Griscom-Russell suggests a once-through "dog-leg" evaporator-superheater.

New approach. We believe that designers of high-temperature sodium heat exchangers and steam generators must solve the thermal-stress problem by using headers and ingenious tube arrangements to get away from "thick and thin" construction. If we could avoid both the thick tube sheets needed to resist pressure stresses and the forces of flowing Na by using circular headers, simple hoop stresses would replace the complex stresses in the flat tube-sheet supported at its edges and pierced by many tube holes.

We believe that a rigid structure is not required to contain low-pressure sodium. If we use high-pressure parts only where they are required in the steam system, we can contain the sodium by a low-pressure container of fairly complex shape but thin cross section while we can contain the high-pressure system in relatively thin-walled containers of circular geometry. This interesting approach, which has not been pursued vigorously by heat-exchanger designers, is embodied in the concept shown in Fig. 9.

Piping and Nozzles

Sodium systems can use thin pipe ($\frac{1}{4}$ in. for 24-in.-o.d. ss pipe vs. 2.75 in. for 14-in.-o.d. Inconel pipe for a typical pressurized-water system) because

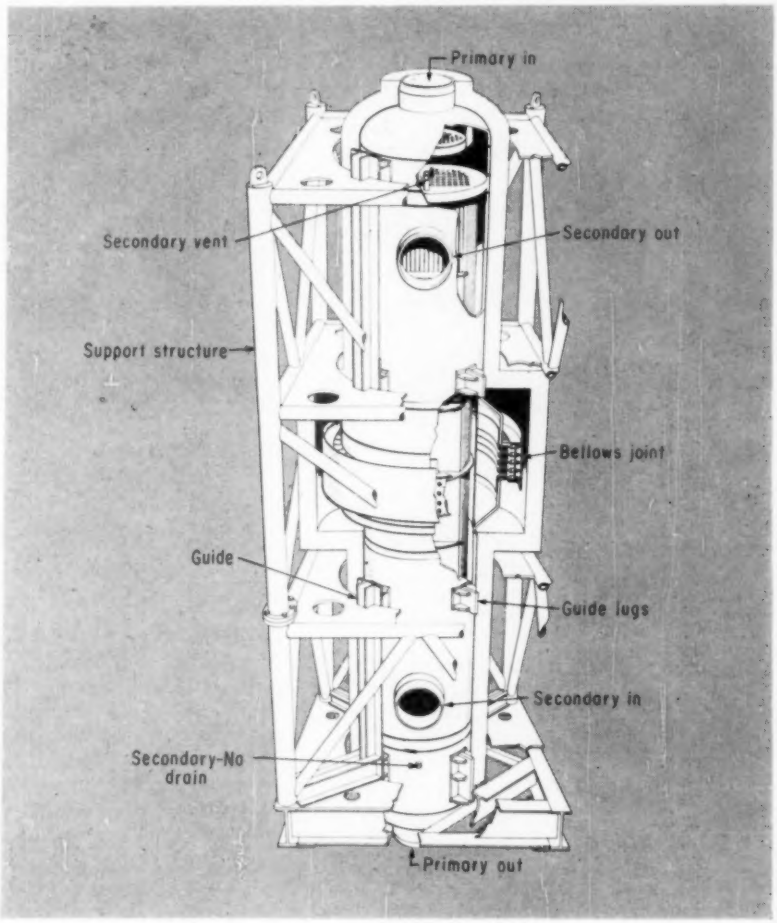

FIG. 6. HALLAM INTERMEDIATE heat exchanger is straightforward vertical shell-and-tube unit with bellows in shell to absorb differential thermal expansion

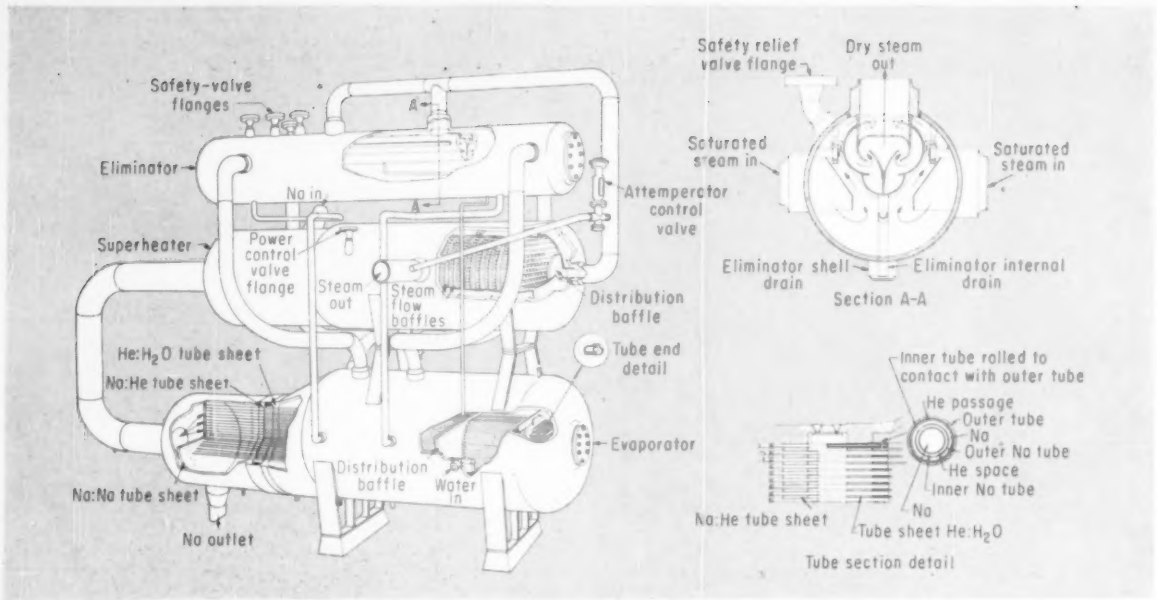

FIG. 7. HALLAM STEAM GENERATOR has bayonet-type duplex-Croloy-tube configuration with 680 bayonet tubes in evaporator and 560 tubes in superheater. To test concept, Mine Safety Appliance Research Corp. operated a 3-Mw 19-tube unit for more than 3,600 hr, including transients more severe than expected at Hallam (7)

sodium is relatively noncorrosive and pressures are low even at high temperatures—which allows low-cost piping.

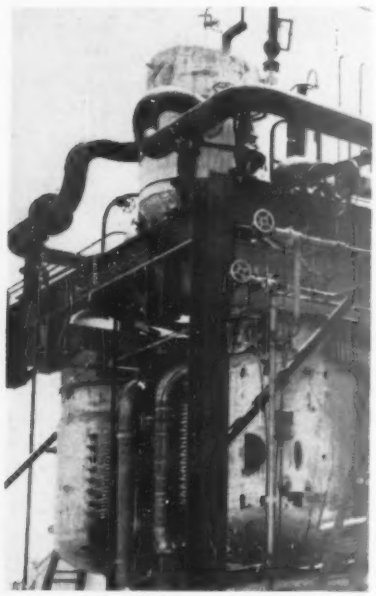

FIG. 8. NATURAL-CIRCULATION double-tube steam generator (shown here without insulation) with "pancake coils" and no tubesheets tested satisfactorily in SRE system (8); Hg between duplex tubes served as leak monitor. Superheater, steam drum and parallel-operating boilers are separate. Originally built by Combustion Engineering for Navy use, its high cost discourages use in large plants

But in building our Large Component Test Loop we have reduced costs further by relaxing specifications on material and cleanliness (*9*). Still more savings can be made by using bellows to absorb the large thermal expansions and stresses characteristic of sodium systems. Our increased confidence in bellows integrity stems from analyses of bellows tests (*10*) and simpler ways to calculate stresses properly (*11*).

Nozzles. Nozzles connect heat-exchange components and piping. As geometric discontinuities, nozzles are stress raisers. Fast temperature transients affect them; thermal stresses due to unequal expansion and contraction (such as occurred in SRE core-tank nozzles) are certain unless thermal sleeves or other design tricks are used.

System layout. Since sodium systems operate through a wide temperature range, their piping must accommodate or resist large thermal expansions. Thermal expansion of piping can cause thrusts and torques on nozzles and component anchor points to go as high as 40,000 ft-lb. So we must design stout components to resist expansion-induced stresses, even though the sodium-system pressure is inherently low. This presents a paradox; in designing stout components to resist heavy stresses we must face the possibility of excessive internal stresses during fast temperature transients. But we can minimize the problem by placing many of the components within a common vessel and allowing them to expand freely, as in EBR-2 and the Enrico Fermi Fast Breeder.

The EBR-2 system contains all primary components in a large core tank submerged in sodium, although the pumps and heat-transfer system are fairly conventional. All Fermi components can be removed from the top of the biological shield without penetrating into shielded galleries. Pumps and heat exchangers are in separate tanks and meticulous attention is paid to accommodating expansion under thermal transients.

Valves

Figure 10 shows valve types we have tested for use in Hallam; also we have tested successfully a new combination valve-and-removable strainer up to the 950° F 10-psi limit of the test loop. By freezing sodium in the valve seat flow is shut off and we can replace the strainer without breaking the pipe, which eases system cleanup and permits cheaper fabrication of piping systems. We also have shown the feasibility of a siphon as a quick-acting flow stopper and blocking valve (*14*).

Generally, valves for sodium-reactor systems have been an annoyance for

several reasons, not the least of which have been cost and reasonable delivery and installation times. Reliable performance is prized because the radioactive environment makes repairs difficult. Also, because of the high radioactivity of sodium from a reactor, we have wanted isolation-valve seats to be leaktight so we can make repairs downstream; we have demanded leaktightness difficult to achieve even in conventional service (zero leakage to atmosphere and usually <1 cm^3/hr across-the-seat leakage under 10–150-psi pressure at about 1,000° F). Still, as is the case with other sodium-system components, valve designs advanced by manufacturers do not differ significantly from valves used in general water or petroleum service. They have expensive hard-face seats in an attempt to reduce seat leakage, bellows seals to prevent stem leakage, and heavy construction intended to combat distortion despite the low sodium-system pressure (and thin pipes on which valves are mounted) and the high thermal stresses during power transients.

Hard-face seats are tight initially, but after foreign materials stick on them they begin to leak. Bellows seals are frequently of unpredictable life, suffer from pinhole leaks, and are more susceptible to operational errors than other types of valves. With all their inappropriateness, sodium valves specified now cost $500–3,000 per inch of valve opening (depending on size and detailed specifications) while common low-pressure valves not specified for sodium service cost $5–50 per inch of valve opening. We must develop a new and more appropriate set of performance specifications for liquid-metal valves.

New approach. Absolute tightness immediately after a leak occurs does not seem essential to limit the effects of a casualty—considerable sodium probably already will have leaked. A "light-weight" valve that stops 99% of the flow would reduce further damage materially. Once flow is limited sharply there would be some time in which to stop it entirely; since sodium freezes at a reasonably high temperature (208° F), completely sealing the valve disk to the seat by casting a seal of frozen coolant becomes a distinct possibility. This would require a cooling system with either forced or natural convection to freeze the liquid metal in the valve-seat area.

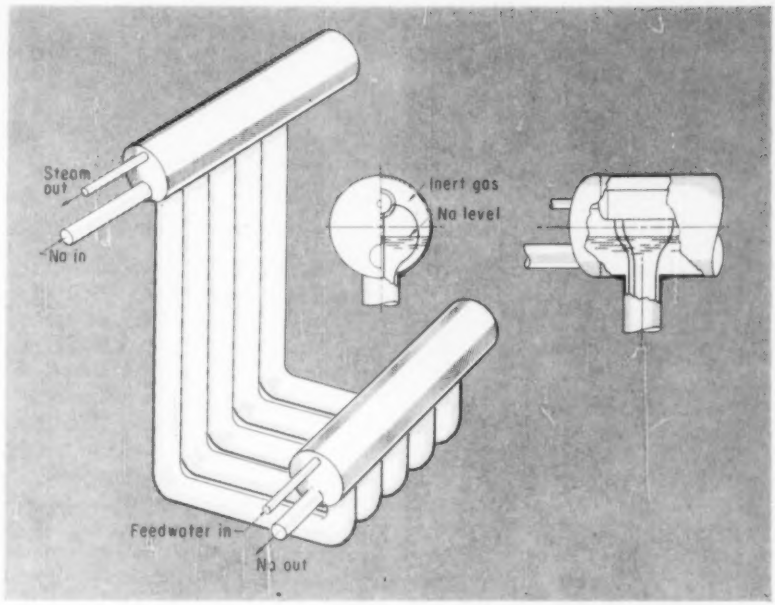

FIG. 9. **OUR PROPOSAL** for an improved steam generator would contain high-pressure steam and water inside boiler tubes, from which steam headers into tubes surrounded by low-pressure Na in counterflow inside thin flexible containers. With guide vanes to assure reasonably straight flow of liquid metal and up to 100 tubes in single shell, high-pressure tubes penetrate sodium shell through flexible connections (such as bellows) to relieve thermal stresses caused by gradients and transients. Thermal shocks would be taken on those components best able to resist them—circular tubes

Bellows seals. Bellows can seal sodium valve stems satisfactorily, but many so-called conventional bellows actually operate above the yield point when fully flexed, so they fail during the first few thousand cycles. But we need bellows on which we can depend for at least 500,000 cycles. We are learning to avoid the disappointing bellows performance encountered in the SRE and other programs (*15*) by resorting to more reasonable design criteria, advanced stress-analysis methods (*11*) and careful tests (*10*). An essential of bellows design is to keep stresses at all points below the yield

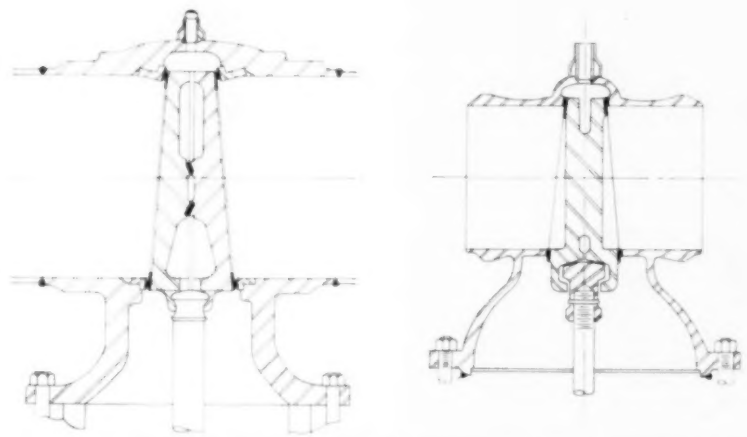

FIG. 10. **GATE VALVES** of types commercially obtained for Hallam [twelve 2-in. Cooper Alloy valves (left) and four 12-in. Crane valves (right)] performed well in thermal-cycling and leakage tests with sodium at 1,000° F and 50 psi (*12*). Steam freeze-seals performed exceptionally well, none leaked. Minor across-the-seat leakage occurred in some valves, but those having "flexible" seats did not leak. Development of a simpler freeze-seal that needs no auxiliary cooling system cuts cost and increases reliability (*13*)

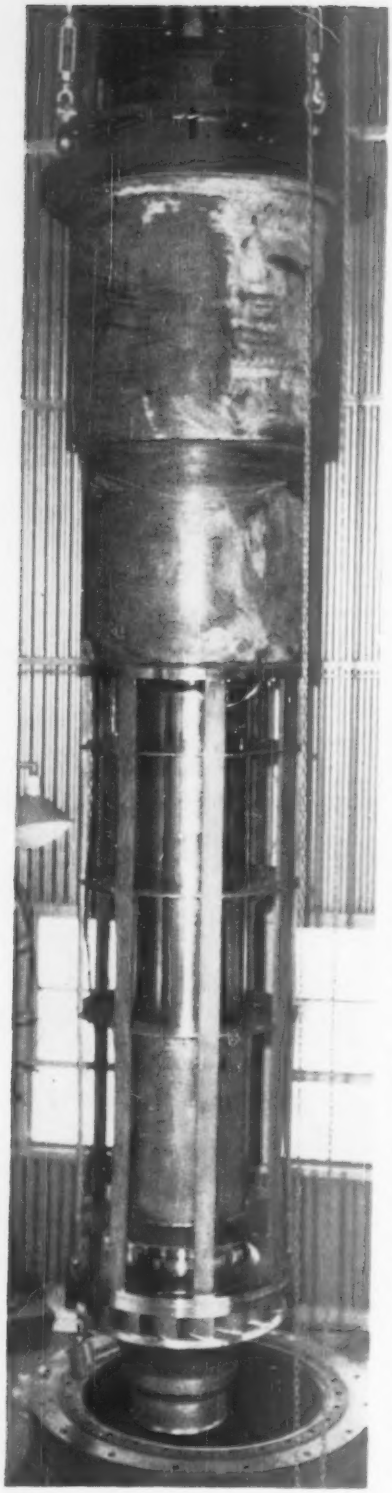

FIG. 11. HALLAM PRIMARY PUMP (Allis-Chalmers unit shown) is mechanical type with free-surface and gas seal; unlike freeze-seal pump it needs no fluid bearing or cooling system; both types satisfactorily pump Na at high head and flow (*16*)

strength of the material. To get reliable bellows, we first design the bellows for the intended service and then design the component in which it is to serve—thus permitting maximum latitude in design of the most sensitive part.

Pumps

Figure 11 shows the type of mechanical pump we will use for the Hallam system. In another step towards improving mechanical pumps for sodium systems we recently added a free-convection NaK system for cooling SRE's main pump freeze-seals; NaK heat will be removed to ambient air or inert-gas gallery atmosphere.

Electromagnetic pumps. The low efficiency* of electromagnetic (E-M) pumps limits their use in reactor main cooling systems, although they find great use in experimental loops and in sodium service systems such as drain lines. Temperature limitations (600° F) of electrical insulation on pump coils continues to block high-temperature operation. We are testing a 3,000-gpm helical-rotor E-M pump (an electric motor drives a d-c magnet to pump Na) that shows promise of high pump efficiency (~40%) while maintaining the advantage of no moving seals. We can vary head and flow by varying the d-c current to the rotating magnet; all moving parts can be removed for maintenance without opening the sodium system.

An eductor we recently tested with sodium performed reliably at 760° F and produced a 15-ft sodium head and 8.5 gpm flow with a motive sodium flow of 14 gpm (*17*).

Instrumentation

Electromagnetic flowmeters for sodium have proven useful over the years, although sodium wetting problems and changes in magnetic flux (due to eddy currents in the Na) have caused erratic performance. Nonlinearity† of signal from large flowmeters (*18*) caused us to develop a meter that measures how much moving sodium distorts a magnetic field.

An improved level gage developed for Hallam measures ±1 in. sodium level without contact and operates continuously at 1,000° F; it has ten 12-in. coils and compares impedance of one coil with another rather than measuring absolute impedance (*19*). Commercial NaK-filled pressure-sensing devices measure sodium pressures greater than atmospheric, but none dependably measure subatmospheric pressure.

Development work on plugging meters for measuring oxide in sodium has reduced measuring time from 30 to 5 min (*20*). Plugging meters can measure as little as 10 ppm oxide, which is more than adequate. Another method holding promise involves measuring electrical conductivity of sodium between a hot and a cold leg. We are developing a device to detect hydrogen in sodium. Since it can indicate a leaking steam generator in a sodium circuit, it will be an "early warning" device for detecting steam-generator failure. A laboratory model detects 1.5 ppm hydrogen in sodium with <10 sec response time.

* * *

The program to develop reliable low-cost sodium components is sponsored by the U. S. Atomic Energy Commission.

* Usually <10%, vs. 80% for mechanical pumps.

† 1% in 12-in. flowmeter, higher when Na is cooler or larger flowmeters are used or flow is high.

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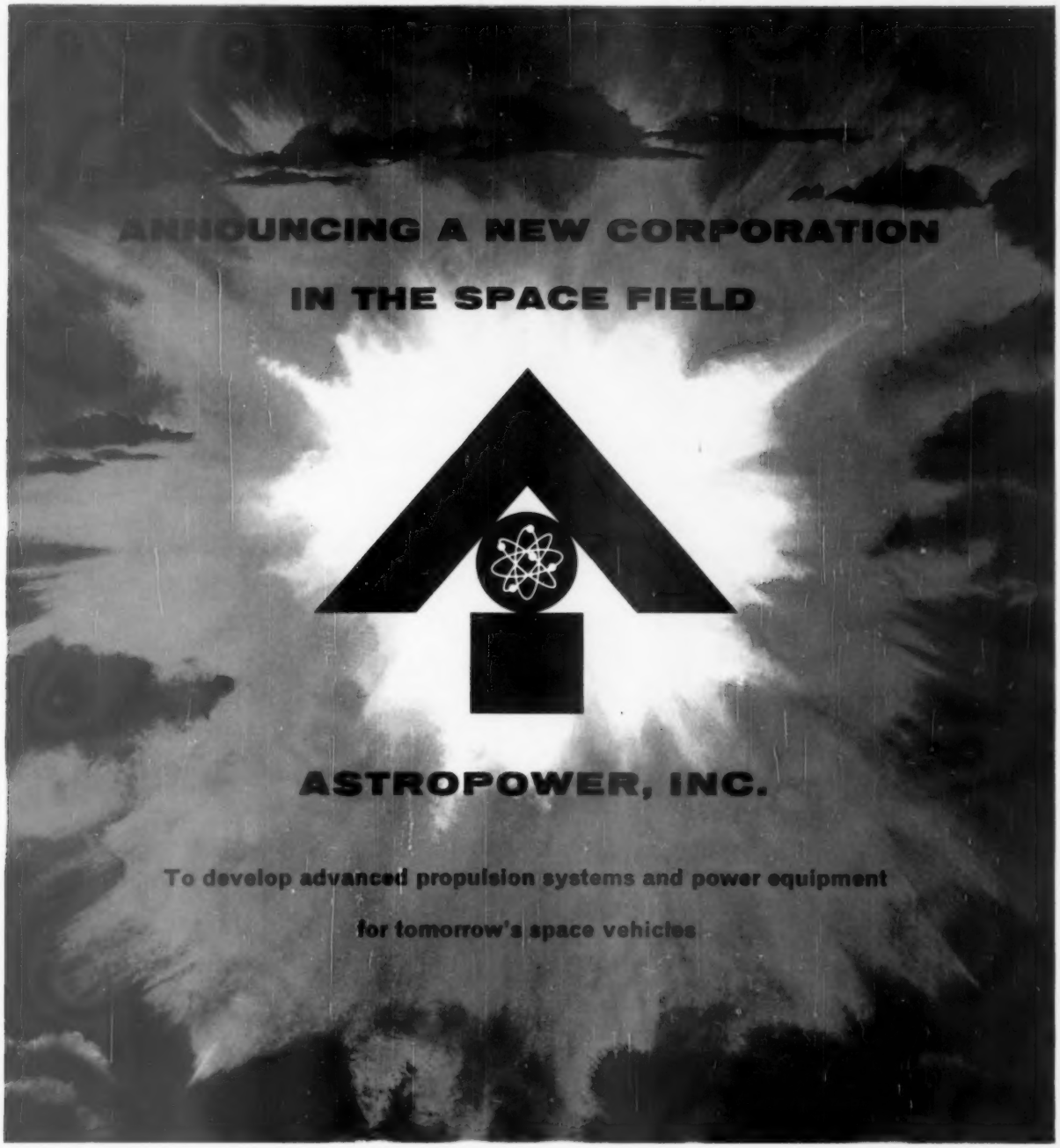
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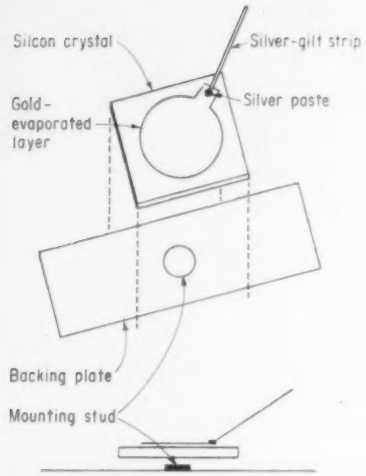

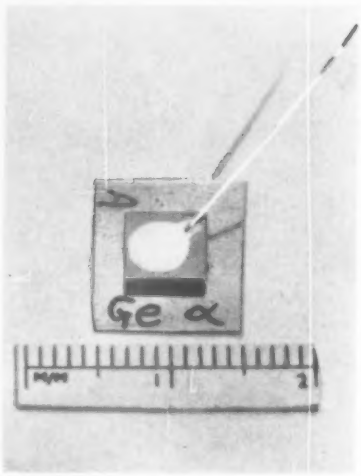

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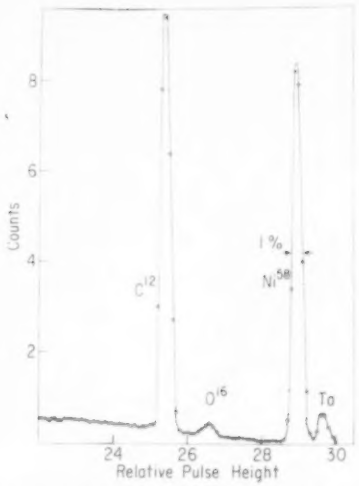

RESOLUTION CURVES for heavy particles

How Harwell Makes Surface-Barrier Detectors

By G. DEARNALEY and A. B. WHITEHEAD, *AERE, Harwell, England*

Work on semiconductor detectors at Harwell was begun following a visit by Dr. Louis Roberts of Oak Ridge National Laboratory in November 1958. He described to us the results (*1*) they had obtained with gold-germanium surface-barrier detectors. In collaboration with Dr. A. B. Whitehead, similar counters were prepared. Towards the middle of 1959 we, together with groups at Oak Ridge (*2*), Chalk River (*3*) and California Institute of Technology (*4*), began to investigate the use of silicon for surface-barrier detectors, to avoid the need for cooling which is presented by germanium. Since then we have concentrated on developing a simple and relatively reliable technique of producing silicon and germanium detectors to a design which is flexible enough to meet the requirements of a variety of experiments (*5*). We'd like to share our techniques with you.

The method recommended for gold-silicon detectors will be described first; the differences in technique for germanium will be given subsequently.

Etching

The crystals are cut to the size required, by a diamond-impregnated saw, and lapped to a fine matte finish with aluminum oxide grit of around 7μ. Care must be taken not to touch the crystals with bare hands at any stage, even before etching. While not essential, it is good practice to clean the crystals prior to etching by boiling for a few minutes in concentrated nitric acid.

The crystal is next put in a polyethylene beaker, about 20–30 ml of CP-4A* etch are added, and the beaker placed in a bath of ice and water to slow the reaction rate and to avoid local temperature rise, which can cause etch-pit formation.

About 5–10 min in the etch should produce a mirror-finish on the silicon surface. Occasional swirling removes the bubbles that accumulate.

Demineralized water is run into the etch, and the crystal is washed by alternate dilution and decanting, avoiding exposure of the silicon to air in the early stages. (In the presence of the strong etch, air produces a brownish-black stain on the silicon.) The crystal is then transferred to a clean polyethylene beaker and washed several more times with demineralized water. This beaker should be used for no other purpose.

* CP-4A consists of:

Concentrated nitric acid	2 volumes
Glacial acetic acid	1 volume
40% hydrofluoric acid	1 volume

Analytical-reagent-purity chemicals are essential for the etch; they should be mixed in clean polyethylene apparatus and allowed to stand for 30 min before use. Fresh etch must be made up for each day's requirements. HF produces serious burns on the skin, and great care must be taken in its use.

Gold-Evaporation

Gold is commonly chosen for this step since it is chemically stable, easily evaporated, gives a high-conductivity film and does not undergo nuclear reactions resulting in charged-particle emission. Other metals can

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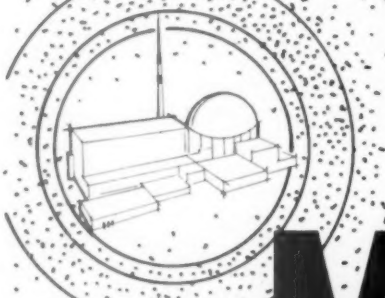

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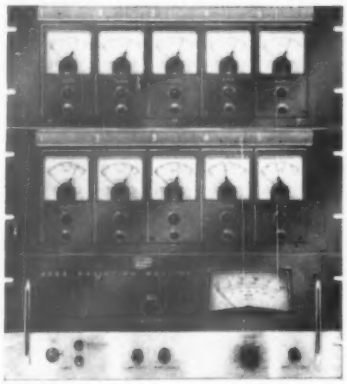

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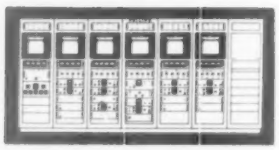
The equipment in use here includes channels for the measurement of both gamma-radiation and fast and slow neutrons in the experimental reactor building, and for the monitoring of water and air contamination.

no living on a volcano



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be used, however, and we have successfully substituted nickel in a situation in which it was difficult to avoid amalgamation of gold with mercury.

A mica mask is prepared for the gold-evaporation; the purpose of the mask during evaporation is to define the area of the detector and avoid deposition of gold on the crystal edges. A convenient shape is the "keyhole" shown in the figure. (In detector use, a circular collimator can be put in front of the counter, so that the front electrical connection is no longer exposed and does not spoil the resolution.)

The crystal is dried on filter paper; the mica is cleaved to give a clean surface, and the crystal is lightly clipped between the mica plates. The surface of the silicon which was uppermost during etching will generally have a better polish; the gold should be evaporated onto this face.

The crystal is mounted in a vacuum evaporator about 3 in. from a strip of molybdenum, bent along its length into a V-section and containing a little gold, say 0.05 gram.

The gold is generally evaporated in a vacuum of less than 10^{-4} mm Hg. For most purposes a film of about 75% light-transmission is satisfactory. This corresponds to 50–100 $\mu g/cm^2$. In cases where a gold layer of minimum thickness is required (e.g., for a fission-fragment detector) it is convenient to have a small quartz strip, with electrodes, alongside the crystal so that the surface resistivity of the deposited film can be monitored. (We are indebted to M. Nobes of AERE for this suggestion.)

The evaporation chamber is then opened and a mask fixed so as to shield all the circular area of the "keyhole" and expose only the area where the front contact is to be made. Gold is again evaporated to build up a thicker deposit of $\sim$500 $\mu g/cm^2$ on this small area. (There is evidence that the organic binder present in the silver paste used later to make contact to the gold occasionally permeates through a thinner layer of gold and causes deterioration of the inversion layer beneath. In such cases it has been found that if the contact and gold are scraped off, and a new contact made elsewhere, performance is restored. The thicker deposit of gold should avoid this trouble.)

The crystal is then removed and

placed on clean filter paper in a covered box for 2–3 days, to allow full development of the surface oxide, which appears to take place through the gold. (We feel that it is better to put the gold on first, to protect the silicon from contamination.)

The crystal is next cemented to the mount, which can take a variety of forms, and may simply be a small disk with fixing holes. Kovar, which has the same coefficient of thermal expansion as silicon, is recommended as a material for the mount. The conducting cement we use is FSP 36 flake silver paste (Johnson, Matthey & Co., London). To avoid having paste flow out to the edges of the crystal, and possibly up the sides, it is best to have a raised stud, or a dimple pressed into the mounting plate, as shown above. This helps to retain a long surface-leakage path between the front gold and the back contact.

The front contact to the gold is made by a short length of silver-gold alloy strip, such as is used for galvanometer suspensions. A kink about $\frac{1}{5}$ mm from the end is made by pressure with a blunt knife-edge, so that the end will lie parallel to the crystal surface. The end is dipped in FSP 36 and attached to the required point, the strip being supported at the other end while the cement sets. The paste should be of such a consistency that it flows slightly onto the gold film, but it is very important to avoid allowing it to flow beyond the gold onto the silicon.

The cement is best hardened by gentle heating, such as on a photographic dish-warmer, at 50° C for about 10 hr.

Variations for Germanium

The procedure for germanium is identical except that (a) the etch is used at room temperature, as the reaction is slower, and (b) the method of making electrical connections is altered, as silver paste tends to fracture after cooling to liquid-nitrogen temperatures a few times (this cooling is necessary when using germanium). It is better to make a solder connection, both to the base of the crystal and to the gold layer, with indium solder (melting point, 155° C). The soldering is carried out on a small hot plate, and both the heating and cooling should be done slowly.

Possible Improvements

It would be preferable to have a more nearly ohmic back contact than

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Surface Barrier Detectors

This article starts on page 72

results from etching the back as well as the front surface. Then, in the procedure above, the silver paste will both adhere better, and give a contact of high surface-recombination velocity.

An improvement in the procedure to accomplish this both for silicon and germanium can be suggested, but so far it has not been tested. The back surface of the crystal can be roughened after etching with a fine abrasive blown by compressed air. Alternatively a rubber suction cup, made of a silastomer that withstands the etch, is used to hold the crystal so that the back surface is protected and is left in its lapped condition. (This idea is due to R. J. Fox of Oak Ridge National Laboratory.)

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New X-Ray Technique Locates Core in Fuel Plates

By CHARLES A. ZIEGLER, J. C. McCUE, J. BRINKERHOFF and D. CHLECK, *Tracerlab Inc., Waltham, Massachusetts*

A new technique that uses coherent X-ray scattering provides a quick production-line method for efficiently and accurately locating the uranium "meat" in clad reactor fuel plates. Since the cross section for coherent X-ray scattering depends on the cube of the atomic number, such scattering can be used to detect large-atomic-number materials imbedded in small-atomic-number media. Thus it is ideal for the fuel-plate problem.

Coherent (Rayleigh) scattering is that scattering which follows the laws of wave optics; that is, it is scattering that takes place without any reduction of photon energy when the separation of scattering centers (here the electrons of a single atom) is small compared to the wavelength. It differs from incoherent (Compton) scattering in that Compton-scattered photons follow the laws of particle dynamics and lose energy in collisions with individual electrons.

Conventional inspection methods for core end-point location include destructive testing and measuring of statistically significant numbers of samples, X-ray radiography, X-ray absorption gaging and X-ray fluorescence analysis (*1-5*). These methods all have serious disadvantages, however. Destructive testing cannot be used on a production-line basis because one can not test every fuel plate and statistical testing methods are unacceptable in quality control of reactor elements. Radiography is usable, but it is inaccurate because of poor contrast at the ends, where cores taper to knife edges, and because of film stretching and shrinking. X-ray absorption gages are also affected by poor contrast; moreover they are influenced by variations in cladding thickness. Although X-ray fluorescence analysis provides accurate end-point measurements, it can not be applied easily to the production line because it requires long measurement times and fairly elaborate and delicate apparatus.

Measurement Technique

Compton-scattered energy loss grows larger as scattering angle increases; Rayleigh-scattered photons, on the other hand, have the same energy regardless of scattering angle. Moreover the cross section for Compton scattering is proportional to the atomic number (Z) of the scattering atoms, while the Rayleigh cross section is closely proportional to Z^2.

These facts suggest that large-angle Rayleigh scattering can be applied to chemical and physical measurements of media with greatly different atomic numbers. The technique has already been successfully applied to measure concentrations of heavy atoms distributed uniformly in a low-Z medium (*6*). Our application extends this technique to locating nonuniform distributions of heavy atoms in low-Z media; and thus to locating the meat in fuel plates.

Our technique is as follows: a collimated polychromatic X-ray source irradiates the sample, and we detect the back-scattered photons at a convenient large angle with a sodium-iodide crystal (Fig. 1). Integral

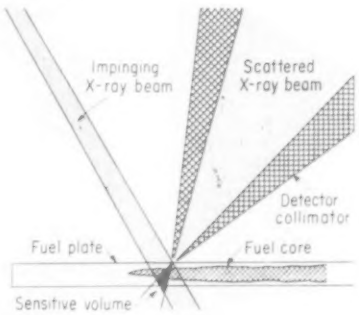

FIG. 1. FUEL-CORE DETECTOR uses coherent X-ray scattering, proportional to cube of atomic number, to recognize high-Z meat in low-Z cladding material

pulse-height analysis eliminates all pulses except those from photons at or near the maximum photon energy of the primary beam. Photons scattered at large angles with this energy can only result from Rayleigh scattering.

Optimum energy. An empirical selection is required to find the most effective X-ray spectrum because on one hand the Rayleigh cross section decreases with increasing energy and on the other hand improved discrimination against Compton scattering at our large angles occurs with increasing energy. We found that an X-ray spectrum peaked at 90 kev gave the best balance between counting rate and discrimination. For this spectrum one needs X-ray-tube operation at ~120–150 kv maximum with moderate filtration. Energies above 96 kev are only a small portion of the total primary flux; this band, however, produces some uranium fluores-

cence at 96 kev, and this enhances the total measured signal flux at this energy. Constant-potential X-ray generation minimizes spectral spread. An adjustable slit collimates the generated X-ray beam.

Experimental Apparatus

We have demonstrated this technique in the laboratory with conventional X-ray generating equipment and detection instrumentation. A modified Keleket Type 150 N X-ray generator with a Machlett Industrial Thermax tube is the X-ray source.

Position. A manually operated screw moves the fuel plate in 0.015-in. steps for accurate longitudinal scanning. The detector receives the back-scattered beam at an angle of 125 deg. Defined by the intersections of the irradiation and detection fields of vision, the sensitive volume is deep enough to intercept uranium at any depth in the plate; on the other hand it is shallow enough to reduce the amount of air-scattered radiation reaching the detector.

Detector and monitor. A 2×2-in. cylindrical sodium-iodide crystal in a Tracerlab RLD-2 scintillation head detects scattered photons (Fig. 2). Meanwhile a separate monitor channel is biased to accept photons in such an energy range that it responds to changes in system parameters rather than the backscattering material. A specially designed detector collimator provides the distance resolution we require to find the end of a fuel core with an accuracy equal to machining tolerances. A scaler operating with preset time gives readout.

Our monitor channel depends on the fact that an energy region in the backscatter spectrum is insensitive to changes in the Z of the scattering medium. Thus one has a means of

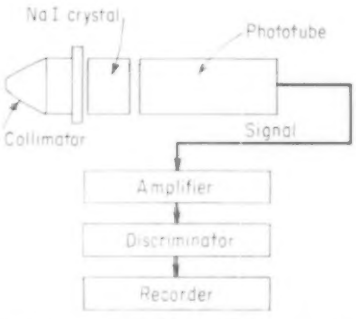

FIG. 2. DETECTOR SYSTEM includes collimator, crystal, phototube and pulse-height analyzer with high integral bias

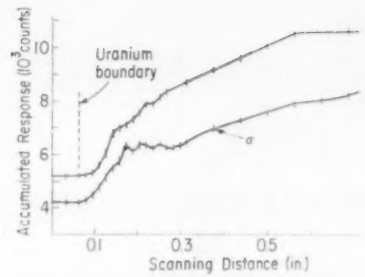

FIG. 3. RESPONSE shows end of fuel plate and taper at end of fuel core. Monitor channel shows only system-sensitivity changes

getting a signal independent of Z but dependent on changes in system parameters. In a production-line instrument one could use such a monitor to make the instrument self-correcting.

The upper curve in Fig. 3 shows the counts obtained in our monitor channel, biased to accept an appreciably lower portion of the energy spectrum than the signal discriminator.

Collimator. One of the chief requirements of the system is a distance resolution in location of the core approaching machining tolerances. Thus we wanted a collimator to provide maximum flux to the detector and make possible a distance accuracy of ± 0.015 in. We settled on a collimator with a single conical hole, an entrance radius of 0.0155 in., an exit radius of 0.75 in. and a length of 3.25 in. Our measurements verify our design calculations and indicate a penumbra radius of ~ 0.015 in. The smallness of our entrance hole improves distance resolution, and we increase primary flux to compensate for the reduction of signal that results.

Core Measurement

The fuel plate we measured was zircaloy-clad with a uranium-zirconium alloy core containing 5–10% uranium; cladding thickness in the fuel region averaged 0.015 in. After the plate was securely fastened to the traversing mechanism an 8-in. length of fuel plate could be scanned.

Figure 1 shows the alignment of the X-ray source, fuel plate and detector collimator. The collimator rests on the surface of the fuel plate so that constant geometry is maintained. Restrictions in our apparatus do not allow us to place the X-ray source closer than 8½ in. to the surface of the fuel plate.

We took initial readings in air just off the end of the fuel plate. As the plate was moved along, the scattered flux increased—first, as the end passed into the sensitive volume and then again as the fuel core came into the detection field.

Results. Our data for two scans parallel to the longitudinal axis of the plate and at two different distances from it are shown in Figs. 3 and 4. As the end of the fuel plate passes under the detector collimator, the system responds as it would to a step function. A measure of the resolution is then obtained by plotting the derivative of the response function for the end of the fuel plate and measuring the distance spread at half maximum. Figure 5 shows the spread at one half the peak value of the differentiated response curve.

The data of these figures permit us to evaluate the counting statistics that we must have for our required distance-measurement resolution. The data in Figs. 3 and 4 require a fractional deviation of better than $\pm 1.5\%$ for a distance resolution of ± 0.015 in. On the basis of counting statistics and the use of the standard deviation to represent our error, we must accumulate $\sim 5{,}000$ counts per measurement for this accuracy (7). We got this count in 120 sec using a ½-ma beam current with the X-ray tube target 8.5 in. from the sample.

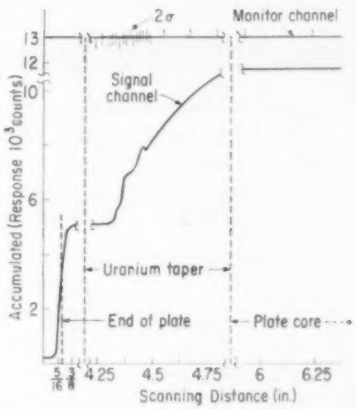

FIG. 4. TWO LONGITUDINAL SCANS of same element show tapered core

These parameters are, of course, characteristic only of our apparatus. One can change the values to predict the performance of a suitably designed system. For example, the distance between the X-ray target and sample could be reduced by a significant factor. Similarly X-ray

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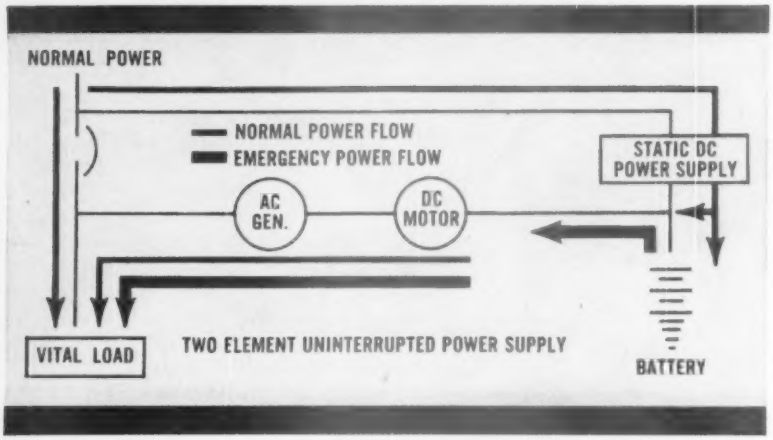

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X-Ray Scattering

This article starts on page 76

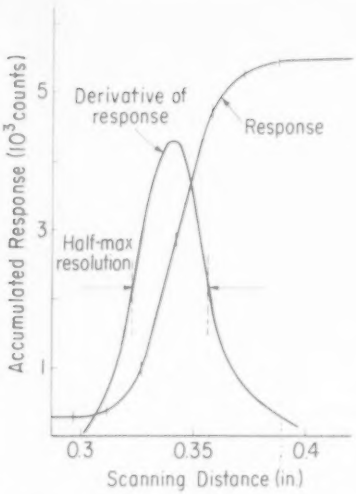

FIG. 5. RESOLUTION OF SYSTEM is width of response-derivative curve where end of plate goes under detector

tubes can operate continuously at beam currents well in excess of ½ ma. Assuming a ¼ reduction in target-sample distance and a thirty-fold increase in beam current, one finds that the accumulated flux will increase by a factor of 480. The time required for each measurement is then 130/480 or 0.25 sec. Thus a serial scan of 1 in. might involve 40 determinations requiring measuring times of ~10 sec. One should therefore be able to attain scanning speeds of several inches per minute.

Verification of Technique

After using our technique to locate the core end of typical fuel plates, we returned the plates to the manufacturer who tested our results by making precise destruction measurements. The agreement between our results and destructive test measurements averaged 0.007 in. If destructive test results are accepted as a standard, the accuracy of our technique is greater than the present manufacturer specification of ±0.015 in.

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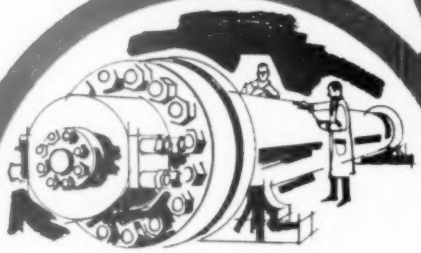

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Optimizing Core Performance

By W. A. SUTHERLAND, *General Electric Co., San Jose, California*

The power-reactor designer seeking to improve core performance would like to remove as much heat as possible at as high a coolant temperature as possible. His limit is frequently the maximum permissible cladding (wall) temperature. A parameter that measures the performance or design effectiveness of a reactor core should, then, involve both the coolant temperatures and the maximum wall temperature. In this article we define such an effectiveness parameter and explain how it can be useful in core heat-transfer analysis, particularly in the preliminary design where a variety of alternatives are being examined.

Effectiveness Defined

In an ordinary heat-exchanger problem, temperature is the independent variable and energy transfer is the dependent variable. Consequently, effectiveness is defined as the rate of energy transfer divided by the maximum rate of energy transfer possible (i.e. a counter-flow heat exchanger of infinite area) (*1*).

$$\epsilon = \frac{(wc_p)_h(t_{h_{in}} - t_{h_{out}})_h}{(wc_p)_{min}(t_{h_{in}} - t_{c_{in}})} = \frac{(wc_p)_c(t_{c_{in}} - t_{c_{out}})_c}{(wc_p)_{min}(t_{h_{in}} - t_{c_{in}})} = \frac{\Delta t_{f_{max.}}}{t_{h_{in}} - t_{c_{in}}} \quad (1)$$

For a reactor core (also electric heaters, etc.) the rate of energy transfer is the independent variable, so that this definition of effectiveness does not apply. However, the form of the equation suggests an effectiveness for the reactor in which temperatures are the dependent variables. Effectiveness for a reactor core means raising the average coolant temperature as high as possible, within the limit of the maximum permissible wall temperature. Hence we propose for a reactor core

$$\epsilon = \frac{t_{out} - t_{in}}{t_{w_{max.}} - t_{in}} \quad (2)$$

To make this definition useful we must express the temperature in terms of heat-generation rates. The coolant temperature rise in a fuel channel is

$$dq = wc_p(t_{z+dz} - t_z) = q(z)\pi R^2\,dz$$

$$t - t_{in} = \frac{\pi R^2}{wc_p}\int_0^{z_i} q(z)\,dz \quad (3)$$

The wall temperature in the channel is

$$Q(z) = h(t_w - t),$$

$$t_w = t_{in} + \frac{\pi R^2}{wc_p}\int_0^{z_i} q(z)\,dz + \frac{q(z)}{P_w}\frac{\pi R^2}{h}$$

The maximum wall temperature will be at the position $z = z_a$ such that

$$t_{w_{max.}} = t_{in} + \frac{\pi R^2}{wc_p}\int_0^{z_a} q(z)\,dz + \frac{q(z_a)}{P_w}\frac{\pi R^2}{h} \quad (4)$$

The effectiveness then becomes

$$\epsilon = \frac{\Delta t_f}{\frac{\pi R^2}{wc_p}\int_0^{z_a} q(z)\,dz + \frac{q(z_a)}{P_w}\frac{\pi R^2}{h}} \quad (5)$$

where Δt_f is the coolant temperature rise through the core, and $q(z)$ is the power density as a function of length in the hottest channel.

In general, the power density will vary in both the radial and axial directions, with the hottest channel at the center. For a given axial profile the performance will be optimum when the coolant temperature rise is the same in all fuel channels. This condition can be met by distributing the coolant among the channels in proportion to the radial power distribution.

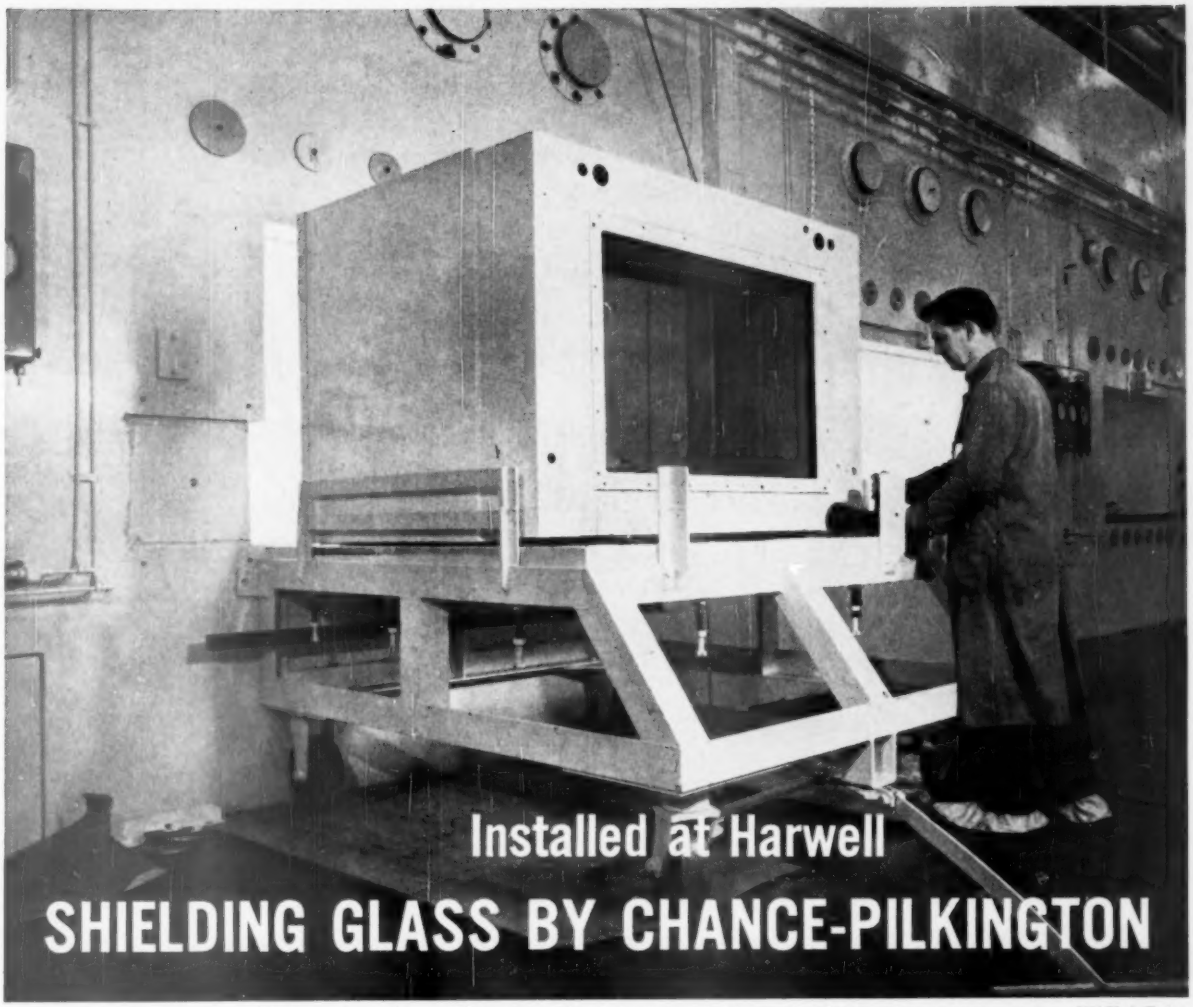
For uniform flow distribution, the effectiveness becomes

Symbol Definitions

Symbol	Meaning	Units
A_t	Heat transfer area	ft²
c_p	Specific heat of coolant	Btu/lb/°F
h	Heat transfer film coefficient	Btu/hr/ft² °F
k	Thermal conductivity	Btu/hr/ft °F
l_c	Core length	ft
N_{tu}	Number of transfer units	hA_t/wc_p
N_{Bi}	Biot number	hr_0/k
N_{St}	Stanton number	h/Gc_p
P_w	"Wetted" perimeter of heat transfer	ft
Q	Heat transfer flux	Btu/hr/ft²
q	Heat generation	Btu/hr/ft³
R	Core radius or fuel channel radius	ft
r_0	Rod radius	ft
r_H	Hydraulic radius	ft
t	Temperature	°F
w	Mass flow rate	lb/hr
z	Axial dimension	ft
z_a	Axial location of maximum temperature	ft

Subscripts

f	coolant		
w	wall	c	cold fluid
r	radial	avg	average channel
h	hot fluid	a	axial



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$$\epsilon = \frac{\frac{2}{R^2}\int_0^R \int_0^{l_c} q(r,z) r\, dr\, dz}{\int_0^{z_a} q(0,z)\, dz + \frac{l_c}{N_{tu}} q(0,z_a)} \quad (6)$$

The figure is a plot of Eq. 6 for various power distributions of interest in reactor design. The abscissa is plotted in units of the dimensionless heat-transfer parameter N_{tu} defined by

$$N_{tu} = \int_0^{A_t} \frac{h}{wc_p}\, dA_t = \frac{h_{avg} A_t}{wc_p}$$

This unit is a convenient measure of the heat transfer "size" of equipment.

Peaking Factors

Core performance analysis is frequently made in terms of the core average conditions multiplied by peaking factors defined by

F_r = radial power ratio
$= \dfrac{\text{hottest channel power}}{\text{average channel power}}$

F_a = axial power ratio
$= \dfrac{\text{peak power in channel}}{\text{average power in channel}}$

F_h = local "hot channel factors" to account for local power peaks, construction tolerances, safety factors, etc.

Since by considering q to be a function of z we have already included the variation described by F_a, we will take the total combined peaking factor as $F = F_r F_h$.

The effectiveness of the *average* channel is

$$\epsilon_{avg} = \frac{\Delta t_f}{\frac{\pi R^2}{wc_p}\int_0^{z_a} q(z)_{avg}\, dz + \frac{\pi R^2}{P_w h} q(z_a)_{avg}} \quad (7)$$

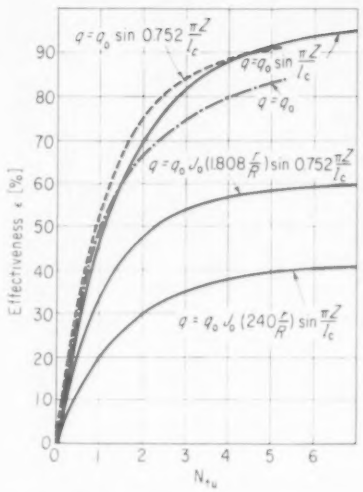
and the core effectiveness based on the hottest channel maximum wall temperature (i.e. $t_{w_{max}}$) is

$$\epsilon = \frac{\Delta t_f}{\frac{\pi R^2}{wc_p}\int_0^{z_a} Fq(z)_{avg}\, dz + \frac{\pi R^2}{P_w h} Fq(z_a)_{avg}} \quad (8)$$

Hence

$$\frac{\epsilon_{avg}}{\epsilon} = F. \quad (9)$$

For instance, if in the figure we think of curve 1 as the core effectiveness and curve 3 as the average channel effectiveness for a reactor core, then according to Eq. 9 the peaking F is the ratio of the two curves or $J_0(r)_{avg} = 2.31$.



CORE EFFECTIVENESS, ϵ, vs. heat transfer parameter N_{tu} for various axial and radial power distributions

Application

The figure shows how the effectiveness depends on power distribution and, since $N_{tu} = l_c / r_H N_{St}$, also on coolant flow and core geometry. For example, given N_{tu}, the average *channel* effectiveness may be determined by Eq. 7. From the design temperatures the *core* effectiveness is found in Eq. 1, and the allowable peaking factors are then specified by Eq. 9. Conversely, N_{tu} and the peaking factors will determine coolant and maximum wall temperature, or the temperatures and the power distribution will determine the number of transfer units N_{tu}.

With oxide fuel elements, the center temperature is sometimes of more concern than the maximum clad temperature. For rod-type elements, the centerline temperature is

$$t_{el} = t_f + \frac{q_{sp}(z) r_0^2}{4k}\left(\frac{2}{N_{Bi}} + 1\right)$$

where the film conductance and clad resistance are lumped in the Biot number N_{Bi}. (The specific power q_{sp} is based on the volume of fuel, as opposed to the power density q, which is based on the volume of the core).

The effectiveness based on t_{el} for

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rod elements has the general form

$$\epsilon = \frac{\frac{2}{R^2}\int_0^R \int_0^{l_e} q(r,z) r\, dr\, dz}{\int_0^a q(0,z)\, dz + \frac{l_c}{N_{tu}}\left(1 + \frac{N_{Bi}}{2}\right) q(0,z_a)} \qquad (6a)$$

As we have mentioned, the optimum performance for a given axial profile occurs when the coolant temperature rise is the same through all fuel channels. This is the condition for the cases shown in the figure in which the power density is a function of axial distance only (cf. curves 1, 2 and 3). From these curves we can see the influence of the axial power profile on effectiveness. For uniform generation (curve 3), effectiveness is slightly higher at small N_{tu}, for the cosine profile in a bare reactor (curve 1) higher at large N_{tu}, and with a reflected reactor (curve 2) higher in the middle values. The differences between these cases, however, are small compared with the gains achieved over curves 4 and 5 in which the temperature rise has not been flattened radially.

With N_{tu} determined in the above manner, we can investigate the pumping power as a function of core size for those cases where pumping is a significant factor. Freund and London (*2*) have presented a method for systematically evaluating core geometries and coolants, and the author (*3*) has combined the effectiveness parameter with this method.

Our assumption of constant film coefficient must be carefully evaluated for detailed core analysis. For example, large variations in local Nusselt number are to be expected around the periphery of nonsymmetrical flow cross sections. This does not preclude the use of an average film coefficient (with an average wall temperature). The resulting variation in wall temperatures (e.g., high in the corners) can be accounted for with a "hot spot" factor F_L applied to $t_{w_{max}}$.

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Reactor to Assay Fuel Proposed at Argonne

Reactor engineers at Argonne National Laboratory propose building of a low-power reactor to check the material content of unirradiated fuel elements. The Fuel Assay Reactor would allow reactor owners to check their fuel against standards to make sure their compositions fall within specifications and to determine their exact reactivity worths. It would also be useful in fissionable-material accounting.

The reactor would have a central reflector in which the elements to be tested would be placed one at a time. A comparison of the reactivity change produced by the test element with that produced by a carefully fabricated standard element of the same type could determine the amount of fissionable material in the test element to one part in a million. Other measurements would determine the distribution of both fissionable and poison material along the length of the element.

The ultimate limit on accuracy in measuring reactivity changes in a reactor is the statistical variation in neutron population in the reactor core. This limit is improved by going to higher power and longer measurement times. One-part-in-a-million accuracy would be the limit for a reactor power of 10 watts and a sample measurement time of 2 min; to achieve this limit and operating conditions the physical dimensions of both reactor and standard specimen would have to be very precisely controlled.

Critical assemblies are now used to assay materials prior to insertion in production reactors. However these are extremely specialized units; in contrast, the reactor proposed here would be useful for a wide variety of shapes, sizes and enrichments. F. H. Martens and H. A. Sandmeier, A proposed fuel assay reactor, ANL-6203 (1960)

Swimming-Pool Reactors Operate at 5 Mw, Reach for 20 Mw

It was once felt that open swimming pool reactors could not be operated above 3–4 Mw, but a power level of 5 Mw has been attained in reactors here and abroad. And 10- or even 20-Mw pool reactors are in design. The "secret" lies in a deeper pool, extra shielding, more cooling for the core, and providing a layer of nonradioactive demineralized water over the pool surface. To get 20 Mw more ingenuity is needed, such as pressurized-water cooling of each fuel element.

Consider the AMF-Atomics-designed pool reactor at Industrial Reactor Laboratories, Inc., Plainsboro, N. J. To cool the reactor, 90° F pool water flows through the core and (at 105° F) into a 33,000-gal holdup tank beneath the pool floor. To allow short-lived radioactivity to decay by 10^3, the "hot" coolant stays in this tank for about 10 min before it is pumped through the heat exchanger and back into the pool. During reactor operation at 5 Mw in the open end of the pool, the hottest fuel plate surface within the core is at 136° F, while an outer fuel plate runs at 185° F (on the natural-convection-cooled side).

To remove radioactive impurities from the water (primarily Na^{24}), some of the water (~60 gpm) from the overflow gutter on one side of the pool passes through a 100-gpm mixed-bed demineralizer. Then the demineralized water is pumped to a gutter on the other side of the pool (this gutter is higher than the one for overflow), from which it sweeps across the pool surface, removing dust and debris and sweeping off radioactive gases. Thus the combination of deep pool (25 ft of water above the core), large pool volume (120,000 gal) for dilution, continual demineralization, downward-flowing coolant and 10-min holdup keep the maximum radiation dose at the water surface above the core to just 16 mr/hr (only 4–7 mr/hr at the top of the pool walls and on the reactor bridge). Ar^{41} concentration in the building exhaust measures only 6% of tolerable values.

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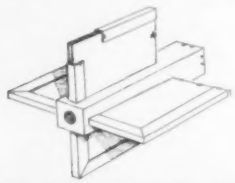
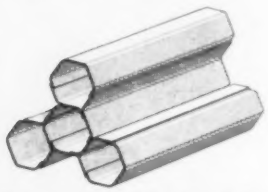
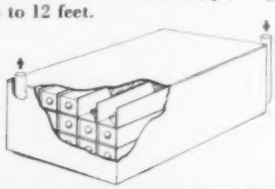


Shut-down Control Rod for Reactors
Assembly of this unit is made by arc welding. All edges of Boral Plate are clad. The center bar is tapped to receive the threaded rod.



Storage Cells for Fresh Fuel
Cells are usually used in assemblies of several fuel units, encased in aluminum or stainless steel cylinders. The Boral shapes should have corner radii of ¾"; length can be up to 12 feet.



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CAN-1: Fog-Coolant Project

By M. SILVESTRI, *Centro Informazioni Studi Esperienze, Milan, Italy*
E. BERNSOHN and G. SOFER
Nuclear Development Corporation of America, White Plains, N. Y.

Fog-cooling—wherein the reactor coolant is a dispersion of water droplets in steam—is under development in a joint Euratom-U. S. project (CAN-1) concerned with its application to a light-water-moderated reactor.

Advantages

The main advantages of a steam-water mixture as a reactor coolant are:

Coolant density is much lower than that of water, which reduces parasitic absorption considerably. At an average coolant quality (weight percent of steam in steam-water mixture) of 40%, the average mixture density at 780 psi is only 9% that of water. Moreover, this essentially eliminates the reactivity danger arising from accidental coolant loss.

Thermal stress is reduced since heat transfer to the coolant is by a constant-temperature process (evaporation of the liquid).

Very high heat-transfer coefficients between fuel and coolant provide good steam conditions with moderate can temperatures.

Direct cycling of coolant into the turbine (after separation of the water) simplifies the plant and improves its operating efficiency.

Negative pressure coefficient of reactivity of a fog-cooled reactor (particularly if initially slightly over-moderated) should provide high inherent stability because of pressure increase with decreasing load.

What Is Fog Cooling?

A reactor fog coolant is formed of water droplets (whose dimensions are on the order of microns) dispersed in steam, rather than steam in water as in the case of boiling-water reactors. Thus, heat is transferred in the two-phase (liquid and vapor), one-component (water) fog system by phase change, an isothermal process. Fog-cooling (called "spray evaporation" by the British) minimizes a serious shortcoming of boiling-water reactors—instability arising from the coupling of reactivity with the variation of the steam-void fraction (1); it also permits much higher heat-transfer coefficients compared with nucleate boiling (30,000–40,000 Btu/hr ft²/°F).

Fog-cooling occurs under certain conditions of steam velocity and quality (the weight percent of steam in a steam-water mixture). At coolant qualities above those that cause nucleate boiling, the steam voids become large enough to cause discontinuous two-phase flow of steam and water "slugs" in a narrow channel. At higher qualities, the steam phase becomes continuous and at high enough steam velocity causes a climbing annular film of water on the channel wall and a partial dispersion of the water as droplets in the steam.

In a fog-cooled reactor, the vapor velocity would be high enough to cause waves in the film from which additional droplets would break off and be dispersed into the vapor stream. Such a fog would typically occur with a steam velocity of 60–100 ft/sec and a steam quality greater than 10%. To form steam of the proper quality, the fog mixture would be formed by injecting steam and water into the fuel channel separately.

The water film is ~10 mils at room temperature and perhaps 1 mil at high temperature. Burnout—in which the film disappears and wall temperature increases—occurs at excessive heat fluxes.

Other Work on Fog Cooling

British work (2, 4) generally corroborates the data published by CISE (5, 8). The British report an increase in heat-transfer coefficient with two-phase flow of one order of magnitude over water and two orders over dry steam. This work was done at low pressures, but current and future work includes heat-transfer tests at high pressures. Similar work is being done in France (9). Russians also reported burnout data in the fog-flow regime (10, 11). Recently, Atomic Energy of Canada Ltd. has indicated plans for studying this coolant in a D_2O-moderated, natural-uranium reactor. A small study of the economics of a fog-cooled D_2O-moderated reactor is also being conducted by NDA for the AEC.

High specific power is attainable since "burnout" can be accepted under transient conditions. Should the burnout heat flux be exceeded, the net result would be a few hundred degrees rise in clad temperature—the heat-transfer wall would not melt.

Problems

The main problems faced in development of the fog-cooled, light-water-moderated reactor are:

Fog must be produced at the inlet of each reactor channel to assure uniform dispersion of the coolant.

Steam-recirculation pumps are required even though the system is direct cycle.

Coolant velocity—60–100 ft/sec—may pose an erosion problem.

Stability of the coolant depends on its quality and flow rate.

At low quality and/or low flow rate, the coolant flow pattern changes from a uniformly dispersed mixture to "annular flow" with the bulk of the liquid flowing near the wall.

Areas of Application

Fog-cooling is applicable to various types of reactors: water-moderated (light and heavy water), graphite-moderated and possibly fast reactors.

In light-water-moderated types, fog-cooling offers several advantages over both pressurized-water and boiling-water reactors. For example, to produce steam in a fog-cooled reactor that has the same characteristics (560 psi and 490° F) as that in the Shippingport power station, the primary-circuit pressure would be only 770 psi, compared with 2,000 psi in Shippingport.

In boiling-water reactors, the specific power is heat-transport-limited by the demands imposed by nuclear stability on the exit quality of the coolant. Fog, however, can be used at much greater evaporation rates because of the smoothness and stability of the flow. Thus inlet conditions of 15–20% quality (and maybe less) and an exit quality of 40–60% are considered reasonably achievable, compared with a quality change of less than 10% in the boiling-water reactor. This would permit higher specific power as well as lower recirculation rates, which might decrease reactor size.

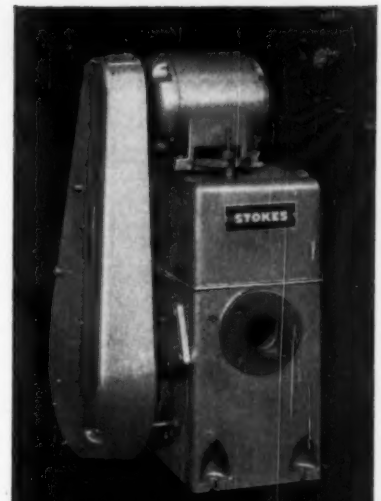
Fog-cooling seems to be a promising approach to nuclear superheat, which could be attained in a two-pass coolant flow. In this application, the low nuclear effect and moderate density change of the coolant in the reactor channel minimizes control problems.

Fog-cooling can help in reactivity-limited systems such as D_2O- or graphite-moderated natural-uranium or plutonium-recycle systems because of the low poisoning effect of the fog compared with that of water. For heavy-water-moderated reactors cooled by light-steam-water fog, thermal insulation between pressure tubes and the moderator allows the latter to be cold and unpressurized, reducing heavy-water inventory.

Fog may find application in graphite-moderated reactors because of its good cooling properties compared with those of gases. It may find application in fast reactors, where minimal moderation is required in combination with high heat transfer and transport. Although fog may not be as good a coolant as sodium from these standpoints, its relatively straightforward technology and direct-cycle applicability make it of considerable interest. Heavy-water instead of light-water fog-cooling could be seriously considered in this application because of its slightly lower moderating power in the fast-neutron region.

Projected Work

The value of steam-water fog as a reactor coolant must be determined



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CAN-1 *This article starts on page 86*

CAN-1 Design Parameters

Net electrical output	200 Mwe
Net plant efficiency	31%
Fuel	UO_2
Coolant	H_2O fog
Core	
Equivalent core dia.	9.75 ft
Core height	9.75 ft
Pressure-vessel i.d.	11.2 ft
H_2O/UO_2 volume ratio	1.3
No. of fuel positions	995
Rods per fuel position	19
Fuel-rod-cladding o.d.	0.500 in.
Cladding thickness	0.025 in.
Cladding material	Zircaloy-2
Average burnup, batch refueling	~10,000 Mwd/ton
Initial conversion ratio	0.69
k_{eff} hot, clean	1.16
Coolant	
Operating pressure	1,000 psi
Pressure drop	65 psi
Inlet quality	15%
Exit quality	35%
Mass. velocity, hottest channel	2.09×10^6 lb/hr/ft²
Max. heat flux, normal conditions	320,000 Btu/hr/ft²
Burnout ratio, (burnout thermal flux)/(max. flux), under worst possible conditions including 20% power transient	1.03

more precisely by extensive experimental and theoretical investigations of its mechanical and thermal properties, together with a study of its nuclear effects in a reactor system.

Three companies are jointly studying a fog-cooled light-water-moderated reactor. Centro Informazioni Studi Esperienze (CISE); Ansaldo Company, Genoa; and Nuclear Development Corporation of America (NDA). This project (CAN-1) is part of the joint Euratom-U. S. research and development program. Initial reactor design characteristics are summarized in the table.

CISE's task in this project is mainly to study two-phase dispersed flow with respect to heat transfer, flow stability and distribution, corrosion and erosion. Three loops are being used in the CISE work:

In a thermal-power-station loop, pressure drops, heat-transfer coefficients and burnout fluxes are being measured in electrically heated ducts cooled by wet steam. Quality is varied over 15–80% at 280–1,100 psi. Several cross-section shapes and modes of heating are being examined.

Flow stability and distribution of a water-argon mixture at ~210 psi and room temperature are being studied in a second loop that simulates reactor-channel flow conditions.

Corrosion and erosion of heated stainless steel or Zircaloy-2 surfaces are being investigated in a high-pressure, wet-steam loop.

Ansaldo is developing special injection nozzles for producing fog at proper quality at the base of the reactor coolant channel. Ansaldo is also constructing a large high-temperature, high-pressure loop to test the effectiveness of these nozzles and moisture-separation devices, which would be used at the outlet of the coolant channels.

NDA's effort is primarily directed towards a detailed analysis of the applicability of fog-cooling to light-water-moderated reactors, including preliminary conceptual design of a reactor and the determination of resulting performance improvements.

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McGraw-Hill Encyclopedia of Science and Technology

(McGraw-Hill Book Co., Inc., 1960, $175.00, 15 volumes)

In these fast-moving times, scientists, engineers and laymen find it increasingly difficult to keep up with the new developments in all branches of science. Not only does the layman want to know more about science and engineering, but the scientist must also keep abreast of developments in his own and related fields. Thus the radiation biologist must know more about nuclear physics; the space scientist must learn how the human body reacts to different environments; the astronomer must study rocket propulsion. The "McGraw-Hill Encyclopedia of Science and Technology" gives the layman or scientist a comprehensive reference to answer his questions. Written within the comprehension of a college upperclassman, the encyclopedia contains more than 100,000 cross-referenced entries, 9,700 illustrations and extensive bibliographies. A one-volume index makes it easy to locate the answers to scientific questions in the fields of physical science, earth science, life science and engineering; the articles in each of these fields are written by eminent scientists and engineers.

An encyclopedia is a difficult thing to review—especially one with the scope of the "McGraw-Hill Encyclopedia of Science and Technology." We have, therefore, asked three members of our editorial staff on NUCLEONICS to look through the encyclopedia and comment on specific branches of the nuclear field: one reviewer covers the encyclopedia as a whole, discussing all branches of science; another reviews nuclear reactors; and a third covers fusion, nuclides, instrumentation and radiation. The reviewers' efforts follow.

The encyclopedia. For the layman with even a more-or-less casual interest in keeping up with the fast-moving technology of our time, this exhaustive and beautifully produced work is a guide that must soon become indispensable.

The definitions and articles are concise, direct and free of jargon; they stick to essentials, yet furnish just enough detail to give some perspective and some feel for the subject. A cursory but systematic interrogation of the book failed to turn up one article that did not contribute new light on the topic, whether already familiar or entirely unfamiliar. The contributors chosen are authorities of first rank in their fields.

The scope of the work is of course amazing. As might be expected of a work that dares to take as its domain all of science and technology, it covers thoroughly not only the major natural sciences but all the -ologies, from geo- to psycho-; all the minor as well as the major engineering branches. But not only can one find a thumbnail review of plane trigonometry or a well-organized summary of the theory and practice of space flight or radar; one can also find a succinct definition of Freudianism, an outline of forest-fire control, a discussion of various approaches to methods engineering, a detailed diagram showing how peanut butter is manufactured.

The illustrations are clear, attractive and illuminating; the typography is inviting; the index is complete and useful. The work is a boon to science and technology.—JK

Nuclear reactors. Five articles in the science encyclopedia sum up the fundamentals of the nuclear-reactor field. They are: *Nuclear power* (2 pages) and *Nuclear fuels* (4 pages), both by J. A. Lane (ORNL); *Reactor, nuclear* (8 pages) by L. J. Koch (ANL); *Reactor, nuclear (Classification)* (3 pages) by H. S. Isbin (Univ. of Minnesota); *Reactor physics* (6 pages) by B. I. Spinrad. In addition there are pieces on more specialized topics such as *Reactor, ship propulsion, Nuclear fuels reprocessing* and *Nuclear rocket.*

Except possibly for the *Nuclear power* piece, the nonspecialist reader will find the five basic articles furnish information in a quantity and depth certainly adequate to satisfy his needs. *Reactor, nuclear*, as a title, is slightly misleading since the piece turns out to be a comprehensive review of the engineering problems of reactor design.

Spinrad's *Reactor physics* is admirably successful in distilling out of this highly specialized subject area a well-balanced and clearly written exposition of the essential concepts.

Before reading, we tested the reactor coverage of the encyclopedia with three sample questions. What is "afterheat"? What is meant by "neutron age"? Under what conditions is one-group neutron diffusion theory valid?

Through the index (under the reference "Heat removal from nuclear reactor") we were led to a two-paragraph discussion in *Reactor, nuclear* of "heat generation after shutdown." Except that the passage did not mention the term "afterheat," it satisfied our curiosity.

The index listing "Age, neutron" referred us directly to *Reactor physics*, which boasted a full column on this subject answering all our questions completely. After looking in vain for "Neutron diffusion," we found the index heading "Diffusion" with a reference under it to *Reactor physics*. The diffusion equation itself or a discussion of its validity did not occur explicitly; however, the paragraph on thermal diffusion area did make reference to the diffusion equation and a one-paragraph section was devoted to the diffusion coefficient.—HLD

Fusion and radiation. When either a scientist from other disciplines or a nonscientist turns to the encyclopedia to learn about fusion or nuclides or instrumentation or radiation, he should be pleased with what he finds. For example, he may look for an explanation of "toroidal pinch." In the index he will find "Toroidal Stabilized Pinch Machine," immediately, under T. This leads to "Pinch effect," and when he reads about toroidal pinch under "Pinch effect," he will find adequate cross references.

If readings of nuclides and instrumentation prompt a curiosity about scintillation counting, the one who is curious will find a good introduction to the subject with, unfortunately, only one rather dull illustration. Cross references lead on to "Low-Level counting," "Particle detector," "Fluorescence" and several other related subjects.

Suppose now that a hospital manager wants to know about radiation sterilization of bandages. "Sterilization" includes an adequate section on "Radiation sterilization." If the reader is a trained engineer of scientist he may be upset by the repeated use of so unprecise and misleading a phrase as "penetrative capacity" to describe penetration. But such apparent lack of scientific sophistication should not mislead him. The actual level of sophistication is high.—RHE

Hot-Atom Chemists Study Nuclear-Reaction Effects

When an atom disintegrates, its transformation can have great and violent consequences in the molecule of which it is a part and in molecules around it. The sudden change of nuclear charge is likely to cause a shaking off of one or many electrons from atom or molecule. Recoil may break bonds, and the resulting fragments may form unusual molecules and ions. Radiation chemists told how they are using mass spectrometers, gas chromatography, radioactivity counting and other types of analysis to study these effects when they gathered recently in Prague under the sponsorship of the International Atomic Energy Agency.

Dissociation of Molecules

An especially modified mass spectrometer at Argonne National Laboratory permits **Sol Wexler** and his colleagues to count fragments when an atom in a gas molecule suffers a nuclear disintegration (*1*). Recent work with organic molecules containing tritium and radioactive bromine leads to a fairly detailed picture of what happens to the molecule when its radioactive atom disintegrates.

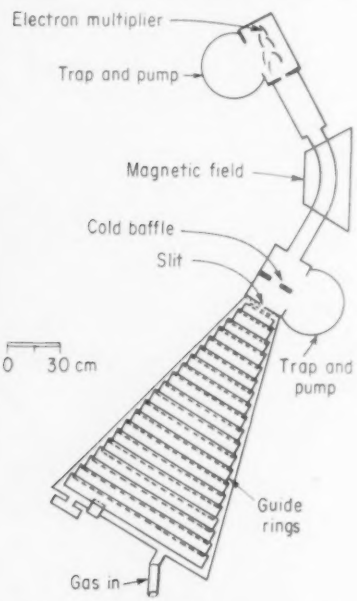

FIG. 1. MASS SPECTROMETER, especially designed, measures fragments produced by tritium disintegrations in gases

The formerly radioactive atom is almost immediately torn away by either recoil or the "shaking" effect, disturbance of electron orbits caused by a sudden change in the nuclear charge. Usually the departing atom takes away its full quota of electrons and leaves behind a positively charged organic fragment. Many of these initial fragment ions appear in the mass spectrum, but often they are left with enough excitation energy to dissociate further.

Spectrometer. Experimental measurements are made with the system shown in Fig. 1. Radioactive gas enters a cone of guide rings where a weak electric field sweeps positive ions toward the analyzer. Most of the accelerating voltage (6,000 volts) is applied to a grid at the narrow end of the cone so that energy differences among ions from different parts of the cone do not broaden the spectrum lines.

Ethane with tritium as one of its atoms produces a dozen types of fragments when it is admitted to the spectrometer. Types are the same, but abundances are quite different from those produced by electron irradiation. When Wexler studies the more complicated gases, he finds that the position of the tritium atom in the molecule usually has little influence on the fragment populations.

Beta emission from Br^{82} in $C_2H_4Br_2$ and CCl Br produces effects identical to those found in the tritium studies. The emitted beta particle has a negligible tendency to remove orbital electrons. Initial organic fragments dominate the mass spectrum, but some of them break up and produce lighter fragments. Doubly charged molecular ions do not show up in the spectrum; a doubly charged ion is apparently unstable and breaks up before it passes through the analyzer.

Negative Ion Molecules

In similar studies **A. Henglein** and G. A. Muccini of the Hahn-Meitner Institut, Berlin, and the Mellon Institute, Pittsburgh, respectively, have been investigating negative ion molecules (*2*). Radiation chemists have been turning recently to ion-molecule reactions for better explanations of reactions they observe than they can get from free-radical theories (NU, March '60, p. 134).

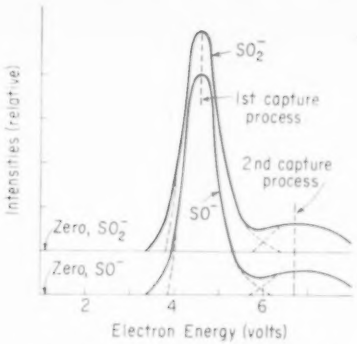

FIG. 2. SO_2^- FORMATION FROM SO^- is indicated by curves showing populations as functions of bombardment energy

Henglein and Muccini modified a standard mass spectrometer to permit investigations of appearance potentials for negative ions and reactions among the ions. In such investigations one admits gas to the source chamber of the spectrometer and then irradiates the specimen with electrons of variable energy. As one increases the energy of bombarding electrons, ions appear in the mass spectrum. An appearance potential is the minimum electron energy that will produce a given ion.

For example, the curves of Fig. 2 show currents of SO_2^- and SO^- when Henglein and Muccini put sulfur dioxide in their spectrometer. Since the curves are identical in shape and since the SO^- ions have some 70 times the population of the SO_2^- ions (the curves are normalized to have the same maxima), the SO^- ion is a precursor of the SO_2^- ion. The shape of each curve indicates that two different capture processes create SO^-; their appearance potentials are 3.9 and 5.9 volts. The following reactions are responsible for the two ions:

$$SO_2 + e \rightarrow SO^- + O$$
$$SO^- + SO_2 \rightarrow SO_2^- + SO$$

Recoil Chemistry

What happens to an atom recoiling from a nuclear disintegration or an

n,γ reaction is important to students of chemical kinetics and chemists who would like to use recoil labeling to make radioactive tracer substances.

With their emphasis on chemical kinetics, **Michael Henchman, David Urch** and **Richard Wolfgang** of Yale University have been studying recoil tritium from the $He^3(n,p)T$ reaction (*3*). In the absence of adequate molecular-beam techniques the best means for studying energetic interactions are these energetic tritium ions, produced at 2×10^5 ev, neutralized at $\sim 10^4$ ev and chemically bound only at energies much less than this. Experiments consist in mixing He^3 with another gas in a quartz ampoule, irradiating with neutrons, separating products by gas chromatography and counting in an internal flow counter.

But recoil substitutions are not limited to small atoms as demonstrated by experiments of **F. Baumgärtner** and **P. Reichold** of Munich (*4*). They have been able to cause substitution of fission-fragment ruthenium and molybdenum for their respective homologs, iron and chromium. Mixtures of ferrocene $[Fe(C_5H_5)_2]$ and U_3O_8 irradiated in a reactor produced $Ru(C_5H_5)_2$; mixtures of chromium hexacarbonyl $[Cr(CO)_6]$ and uranyl acetate produced a substitution of molybdenum for chromium. In each situation the analysis is simplified by knowledge that only one fission product forms a stable compound by substitution.

Recoil experiments of a different nature, performed by **W. S. Koski, H. Schmied** and **W. C. Perkins** of Johns Hopkins University, explored the substitutions that occur when energetic N^{13} atoms are directed at atoms of methyl bromide, methyl chloride and carbon tetrachloride (*5*). Energetic deuterons produced N^{13} recoils from the $C^{12}(d,n)N^{13}$ reaction. Gas chromatography with both thermal-conductivity and radioactivity detection showed that the predominant products were cyanides.

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Papers presented at the Symposium on the Chemical Effects of Nuclear Transformations, Prague, October 24–27, 1960, with numbers assigned to them at the symposium:

1. S. Wexler. Dissociation of molecules by nuclear decay of constituent atoms (CENT/52)
2. A. Henglein, G. A. Muccini. Mass spectrometric studies of reactions of negative ions with neutral molecules (CENT/27)
3. M. Henchman, D. Urch, R. Wolfgang. On the chemistry of recoil tritium (CENT/50)
4. F. Baumgärtner, P. Reichold. Recoil labeling in mixtures of solids by resonance neutrons and nuclear fission (CENT/33)
5. W. S. Koski, H. Schmied, W. C. Perkins. Chemistry of N^{13} recoils in some carbon compounds (CENT/53)

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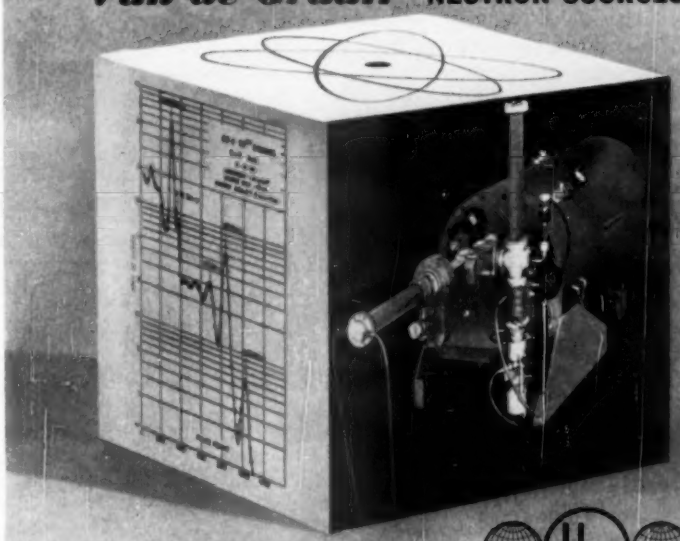

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Laboratory Evaluations of Nine Water Tracers

By R. J. HEEMSTRA, J. WADE WATKINS, and F. E. ARMSTRONG

U. S. Department of the Interior, Bureau of Mines, Bartlesville Petroleum Research Center, Bartlesville, Oklahoma

Radiotracers are needed to follow subsurface flow in the water of petroleum reservoirs. Two principal requirements for such tracers are low loss through contact with solid petroleum-reservoir materials and stability in brine solutions (*1–3*). To test several likely substances against these standards we have made laboratory tests for stability and losses from solution when the tracers pass through geological cores. Measurements of radioactivities in both the solution being recycled and the drained core material offer a significant comparison of the different tracers.

We tested 11 different chemical substances, each containing one of the following nine radionuclides: tritium, I^{131}, Rb^{86}, Ir^{192}, Cr^{51}, Sb^{124}, In^{114}, Co^{60}, Ce^{144}. All of our tracer nuclides were chelated with ethylene diamine tetraacetic acid (EDTA) except tritium, iodine and rubidium. We also tested iridium as the hexachloroiridate complex and chromium as the hydrated cation. Iodine was used as carrier-free iodide anion and also evaluated separately with a carrier. In one solution tritiated water and I^{131} were tested simultaneously.

On the basis of our criteria, our results show that three of the tracers tested should be useful water tracers: tritiated water, I^{131} as the iodide ion, and Sb^{124} complexed with EDTA. $Rb^{86}Cl$ may also be usable, but it shows a lag in breakthrough concentration so that arrival times may not be comparable with those indicated by other tracers that have greater breakthrough concentrations and more rapid breakthroughs. Utility of the other tracers is questionable.

Requirements

Tracers are lost from solution because of adsorption, ion exchange, diffusion, dilution, hydrolysis with resultant precipitation and filtration, and possibly other physical and chemical reactions.

In general, anions and complexes are subject to less loss than cations. Since many metals form stable water-soluble complexes with EDTA but few radionuclides are available that can be prepared readily as stable anionic complexes, we decided to evaluate several metallic radionuclides as EDTA complexes. Some similar early work with Conasauga shale has been reported (*4*).

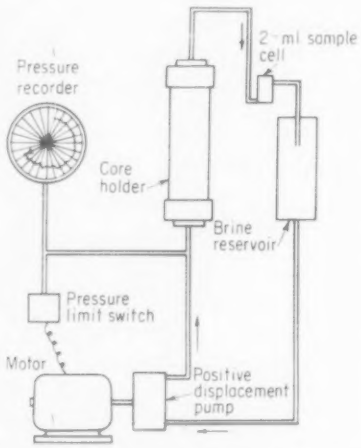

FIG. 1. WATER-TRACER TEST pushed labeled brine through sandstone and measured breakthrough and accumulation of radioactivity in effluent and core

Experimental

To test each of our tracers we labeled a brine solution, forced it through a test core and measured both the activity of the solution emerging and the activity in the core after the solution had been circulated through it. We chose tritiated water as a comparison standard because of its small adsorption loss.

Rock cores. All cores used in the flow tests were cut from the Roubidoux sandstone formation of Pennsylvanian age. The cores, 4-in. in length and 1½-in. in diameter, were thoroughly dried and were free from crude-oil residues. Average porosity was ~10%; permeabilities ranged from 120 to 280 millidarchys. (A porous structure has a permeability of 1 darcy if a fluid of 1 centipoise viscosity flows at 1 cm^3/cm^2 under a pressure gradient of 1 atm/cm^2.) All tracers were tested in a synthetic brine containing 50,000 ppm of sodium chloride adjusted with phosphate buffers to a *p*H of 7.5.

It would be most interesting to test

Choosing a Water Tracer

In addition to the criteria discussed in this article, others that are important in choosing a water tracer are half-life, type and energy of radiation, cost and availability. All of the tracers tested are readily available. The disadvantage of I^{131} is its 8-day half-life. Conversely, the 5.2-year half-life of Co^{60} is undesirably long for a hard-gamma emitter. Sb^{124} and Rb^{86} have half-lives of 60 days and 19.5 days, respectively. Three to five half-lives represents a reasonable detection interval for a tracer. Therefore I^{131} should be detectable for about 6 weeks, Ru^{95} for 14 weeks, and Sb^{124} for 10 months. All of the tracers tested except tritium emit gamma rays that are detectable with logging tools (*7*) and portable monitors (*8*) developed for this purpose.

Tritium, I^{131} and Rb^{86} cost so little that one can economically use as much as several curies of them in field tests. The cost of Sb^{124} ($3.00/mc), however, approaches the range of economic impracticability and the ruthenium isotopes, which as the ruthenate complex give promise of being useful water tracers, were not included in the tests because of their excessive cost ($10/mc for Ru^{103} and Ru^{106}).

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all of the tracers showing promise with other rock types. The time required to do so would have been prohibitive, however, in view of the many reservoir rocks having different chemical and physical characteristics. The formation from which our cores were cut is fairly representative of many oil-producing sandstones with respect to porosity, permeability and content of clay minerals.

All of our data were obtained by passing the tracer solutions through dry sandstone cores with the exception of carrier-free KI^{131} in the first test. In this test we used a core previously saturated with unlabeled brine solution.

We mounted the cores in a modified Hassler core holder (*5*) and placed them in the recycling system of Fig. 1. In some of the early flow tests the tracer solutions were recycled at a constant flow rate by a Milton Roy "Minipump." In later tests we used a Lapp LS-20 Pulsafeeder. End plugs to the Hassler core holder and all of the connecting tubing and fittings were made from plastic to eliminate corrosion of the system and consequent plugging of the cores. Valves and pump head were of stainless steel; solution reservoir and sample cell of Pyrex; a pressure-limit switch in the system guarded against accidental bursting of the plastic tubing.

Counting. We measured tritium activity with a Packard Tri-Carb liquid-scintillation spectrometer and radioactivities of all other nuclides with a 1¾- × 2-in. NaI well-type crystal. Solution activities were determined from 1-ml samples counted in 1-dram shell vials.

Core activities were measured by placing a ⅛-in.-thick cross section cut from the core in a plastic cup directly over the scintillation crystal. Each cross section was ~4% of the total core.

Procedure. We evaluated tracer loss by a three-stage method:

First, a labeled brine solution from a reservoir was passed through the sandstone core at a constant flow rate of ~3 ml/min, and the effluent sampled periodically for radioactivity determinations. Effluent tracer concentration was calculated as the ratio of effluent activity to initial solution activity and plotted against effluent volume to make a "breakthrough" curve (Fig. 2).

Second, the collected effluent was returned to the reservoir and then recycled continuously while we measured samples periodically for radioactivity.

Third, we removed the cores from the drained system after the flow tests and cut thin cross sections from them. The sections were weighed and specific activity of each section was determined with the scintillation counter. We used the ratio of the activity of a core section to the initial activity of brine as the relative specific activity of the core section.

TABLE 1—Breakthrough Data for Tracers in Sandstone Cores

Tracer	*Breakthrough concentration**	*Maximum concentration**	*Cumulative effluent at maximum concentration* (*ml*)	(*pore volumes*†)
Tritiated water	0.96	1.00	15	1.3
Carrier-free KI^{131}	0.84	1.00	18	1.5
Sb^{124}-EDTA	0.81	1.00	28	2.3
$Rb^{86}Cl$	0.15	1.00	55	4.6
Co^{60}-EDTA	0.82	0.98	65	5.4
Ce^{144}-EDTA	0.02	1.00	90	7.5
Ir^{192}-EDTA	0.80	0.99	70	5.8
In^{114}-EDTA	0.47	0.92	70	5.8
Sodium chloroiridate (Ir^{192})	0.79	0.83	32	2.7
Cr^{51}-EDTA	0.44	0.61	45	3.8
Cr^{51} hexahydrate	0.00	0.14	—	—

* Ratio of effluent radioactivity to initial solution radioactivity.
† Average effective pore volume of cores is 12 ml.

Concentrations of our tracer nuclides and their stable carriers were as follows: iridium, chromium, antimony, and cerium, 1 ppm; indium, 3 ppm; cobalt, 0.1 ppb; rubidium, 2 ppb.

Performance as Tracers

An ideal water tracer, as determined by our method, would exhibit an initial effluent radioactivity equal to the original solution radioactivity and be subject to no loss in the core. In a near-ideal situation one would expect that any slight radioactivity retained in the core would be fairly uniformly distributed throughout and that the loss was caused primarily by adsorption.

Table 1 presents a summary of the data on the breakthrough of radioactivity in 11 tests of our nine nuclides. Figure 2 is a plot of data for seven of the tests; data from three other tests are plotted in Fig. 3. As

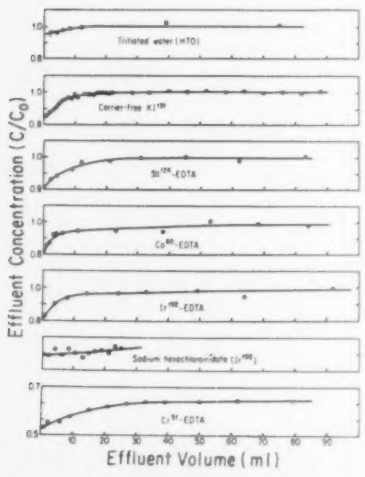

FIG. 2. BREAKTHROUGH CURVES show ratios of effluent activity to activity of brine solution as it enters core

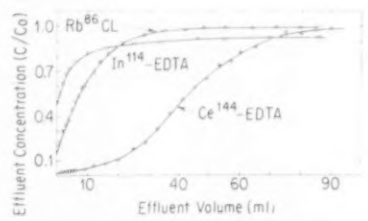

FIG. 3. LAG IN BREAKTHROUGH is demonstrated by $Rb^{86}Cl$ and Ce^{144}-EDTA in comparison with faster breakthrough of In^{114}-EDTA tracer

no more than 1% of the Cr^{51} hexahydrate was detected in the effluent from the core in which it was tested, the breakthrough data from that test are not presented in graphical form.

With dry cores the tracer concentration in the first effluent should represent, approximately, the lag in arrival of the concentration front of each tracer. A tracer front that moves through the core much more slowly than the liquid front would show a considerable lag in its breakthrough curve. A good example of this lag is seen in the breakthrough curves of $Rb^{86}Cl$ and Ce^{144}-EDTA in Fig. 3. Ion exchange probably is the principal reason for the delay in arrival of these tracer fronts.

Breakthrough concentrations of tritiated water and carrier-free KI^{131} (Fig. 2) indicate that little loss of tracer occurs on initial contact with the cores. Sb^{124}-EDTA exhibits similar characteristics although the lag in reaching 100% effluent concentration is slightly more pronounced.

Although both $Rb^{86}Cl$ and Ce^{144}-EDTA also reached effluent-solution concentrations of 100% and the eventual effluent solution concentrations of Ir^{192}-EDTA, Co^{60}-EDTA, and In^{114}-EDTA range from 99% to 92%, the lags are much more pronounced with these tracers. Sodium chloroiridate labeled with Ir^{192} did not exhibit a pronounced lag although the initial concentration of 79% increased only to 83% after the passage of 2.7 pore volumes of effluent. The indicated performance of cationic Cr^{51}, both as the EDTA complex and the hexahydrate, was entirely unsatisfactory.

Recycling tests were continued after the breakthrough tests until the slopes of plots of concentrations of tracer in the effluents remained essentially constant. Table 2 presents the data from recycling. The apparent 5% loss of carrier-free KI^{131} is explained by the use of a saturated core for this experiment. Dilution of the original 250 ml of solution by the pore volume of 12 ml of nonradioactive brine caused a reduced specific radioactivity of effluent and an apparent loss of tracer. Actually, essentially no loss of I^{131} occurred throughout this test.

The column giving the rate of loss of tracer per liter of effluent was tabulated from calculations of tracer loss after breakthrough. Thus, Cr^{51} hexahydrate shows a comparatively small recycling loss per unit volume. The initial loss on breakthrough, however, was excessive. Conversely, Cr^{51} chelated with EDTA was subject to a large initial loss (39%) although no additional detectable loss occurred in recycling 88 liters of solution through the core.

Figure 4 represents graphically the total loss of tracer in the 11 experiments as a function of cumulative effluent. Horizontal straight-line portions of the curves show tracers that reach and maintain equilibrium in solution when in extended contact with sandstone.

Stability of a tracer material in solution is an important characteristic, especially when the tracer contacts a great area of reservoir material for a long time. Continuous recycling made variable the length of time that the tracer was in contact with the core material. The core

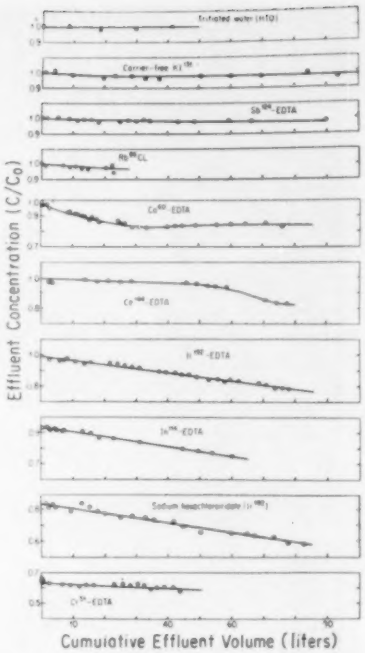

FIG. 4. CONCENTRATION OF TRACER in continuous recycling becomes level when (and if) an equilibrium is established with material of the test core

also served as a continuous filter for the solution, thereby removing any hydrolysis products from the tracer as they were formed. Only tritiated water, carrier-free KI^{131}, Sb^{124}-EDTA, and $Rb^{86}Cl$ show desirable stability characteristics on these plots. In similar experiments reported by Halevy and co-workers (*6*), iridium was an unsatisfactory tracer because of dissociation of the chloroiridate complex and replacement of iridium in the EDTA complex by calcium and magnesium.

It also was of interest to determine the distribution of activity through the core material. By cutting thin sections from the core and measuring residual radioactivity of each section, we could determine the regions of greatest tracer concentration. For tracer materials with great instability or those that hydrolyze easily, the core-inlet sections would be expected to have much residual radioactivity.

In general this was true; tracers subject to greatest losses from solution, resulting in high total residual radioactivities, exhibited the greatest retention at the inlet ends of the cores. Considerable scattering of the data is evident, however, caused by poor reproducibility in the counting assembly. With tracers that show hydrolysis and precipitation as well as adsorption or ion exchange as causes

TABLE 2—Loss of Continuously Recycled Radioactive Tracers

Tracer	*Effluent volume (liters)*	*Rate of loss after breakthrough (%/liter)*	*Total loss (%)*
Tritiated water	41	0	0
Carrier-free KI^{131}	116	0.04	5*
Sb^{124}-EDTA	180	0.01	2
$Rb^{86}Cl$	23	—	5
Co^{60}-EDTA	206	0.28	16
Ce^{144}-EDTA	78	0.20	17
Ir^{192}-EDTA	219	0.10	23
In^{114}-EDTA	120	0.16	25
Sodium chloroiridate (Ir^{192})	200	0.16	43
Cr^{51}-EDTA	88	0	39
Cr^{51} hexahydrate	28	0.14	99

* Wet core used; initial dilution of solution activity by non-radioactive brine in core caused reduced specific radioactivity and apparent tracer loss.

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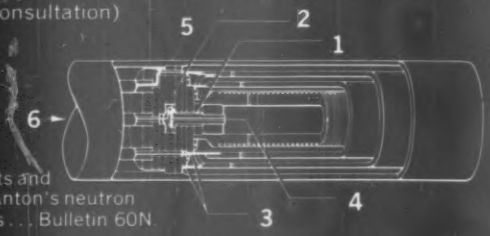

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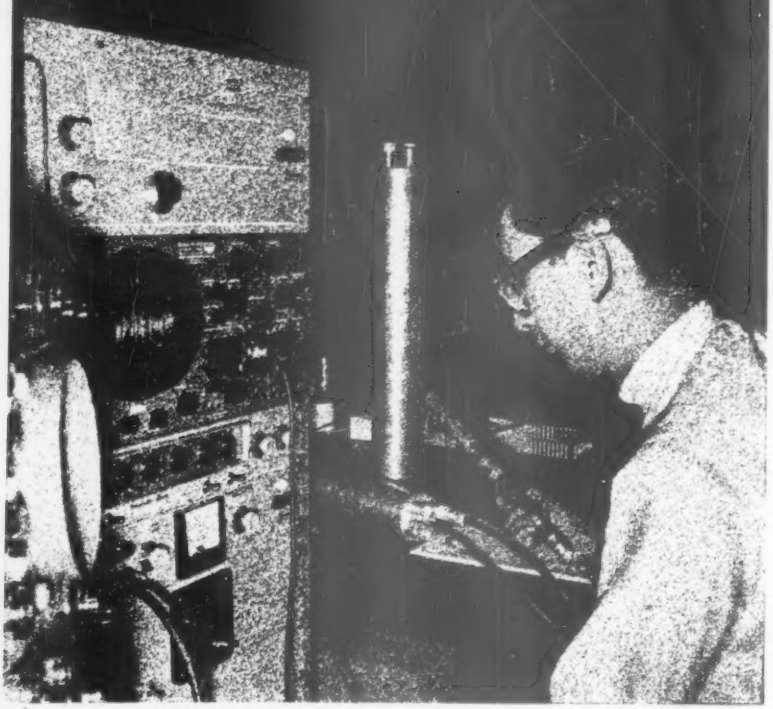

*Reg. app. for.

Water Tracers

This article starts on page 92

of tracer loss, specific radioactivity of the inlet section of the core was 2–3 times the specific radioactivity of the next section. For other tracers with which hydrolysis appeared to be no particular problem (Sb^{124}-EDTA and Co^{60}-EDTA), radioactivity was fairly well distributed through the entire core.

Tritium as Tracer

The soft beta of tritium cannot be detected by an external detector and no present methods of subsurface detection or simple and inexpensive continuous monitoring are available. Nevertheless, for conditions of long transit time, it is believed that tritiated water probably is the best water tracer available. Other than apparent loss from dilution and diffusion, which is to be expected with any water tracer, the only probable loss of any consequence from using tritiated water might be caused by isotopic effects. The results of our laboratory test with tritiated water indicate little preferential adsorption.

Tritium in the tracer water molecule can exchange with hydrogen atoms naturally present in reservoir fluids. As only adsorbed or otherwise immobile molecules can cause loss of tritium through such isotopic exchange, however, the loss from this cause is probably small. Although Kaufman and Orlob (*9*) report a definite retardation of a tritiated water front as compared with the travel of chloride ion, experiments by Finkelshtein and colleagues (*10*) indicate success in using tritiated water for tracing water movement through a dense sandstone, without noticeable time lag.

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New Branching Ratio for Kr^{85}

By KLAUS W. GEIGER, *National Research Council, Ottawa, Ontario, Canada*
JANET S. MERRITT and JOHN G. V. TAYLOR, *Atomic Energy of Canada Ltd., Chalk River, Ontario, Canada*

Krypton-85 is being used more and more as a gaseous tracer, a beta-gage source, an index of the quantity of fission off-gases, and for other purposes that require accurate quantitative assay. The usual way to assay a Kr^{85} sample is the difficult and cumbersome one of internal-gas beta counting, in which the krypton must be mixed with the counter gas. This method suffers from special problems if the sample is contaminated (*1*).

A simpler method is to determine absolute gamma emission with a scintillation spectrometer that has a known photopeak response (*2*). Another is to compare the Kr^{85} gamma emission (0.517 Mev) with annihilation radiation (0.511 Mev) from a positron emitter of known intensity. But to use either of these gamma-counting methods one must know the branching ratio: the fraction of Kr^{85} decays in which a gamma photon follows the beta (Fig. 1).

We have redetermined the branching ratio by making absolute beta and gamma measurements of Kr^{85} samples; our result is $0.46\% \pm 0.04\%$. Our value is lower and more precise than the previous value of $0.65\% \pm 0.15\%$ (*3*). The table (p. 98) shows errors introduced by our method.

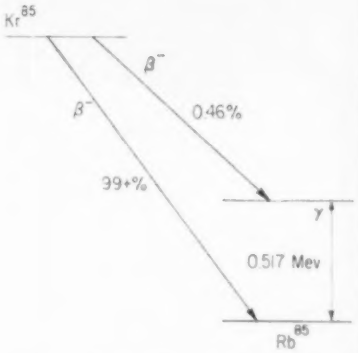

FIG. 1. DECAY SCHEME FOR Kr^{85} shows new branching ratio. 0.46% of Kr^{85} decays have beta emission followed by gamma photon emission

Gamma Measurements

In making absolute-intensity measurements of Kr^{85} samples, our first step was to measure the intensity of the 0.517-Mev gamma line using 0.511-Mev positron annihilation radiation from Na^{22} standards to provide a calibration for the Kr^{85} samples. We made measurements with a 2 × 2-in. NaI scintillation spectrometer; the sources were placed ~6 cm from the front face of the scintillation crystal. An 0.5-gm/cm² lead filter in front of the crystal reduces the large number of low-energy bremsstrahlung pulses that come from the beta radiation of Kr^{85}.

Kr^{85} measurement. The Kr^{85} was kept in cylindrical glass flasks (1.3-cm dia, 3-cm length). So that radioactive contamination with other fission-product gases would decay we had stored the active fission-product gas (>99% pure krypton) for one year. After putting several microcuries of Kr^{85} in each flask we added sufficient inactive krypton to bring the flask pressure up to about 1 atm.

Three Recent Values for Kr^{85} Branching Ratio

Value (%)	*Researchers*	*Date released*	*Published in*
0.46 ± 0.04	Geiger, Merritt, Taylor	4-8-60	this article
0.36 ± 0.08	B. F. Rider, J. P. Peterson (GE Vallecitos)	8-1-60	GEAP-3496
0.38 ± 0.03	W. S. Lyon (ORNL)	9-23-60	*Nuclear Sci. and Eng.* (in press)

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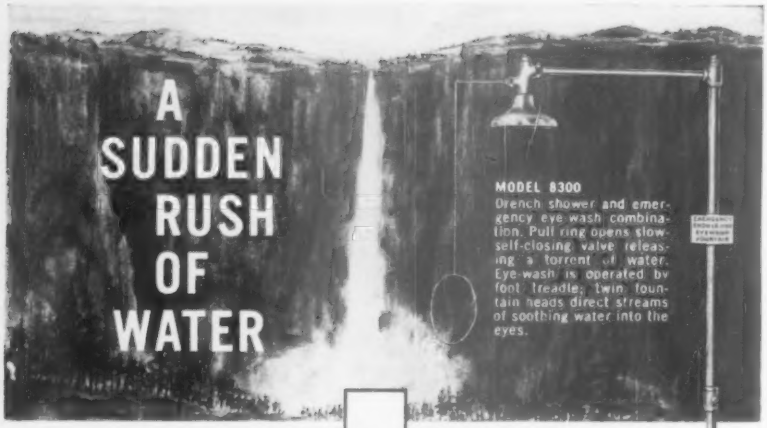
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Na^{22} calibration. To get standard sources of Na^{22} with geometrical properties similar to the Kr^{85} samples, we filled glass flasks, identical to the Kr^{85} flasks, with absorbent cotton, added 0.05 ml of Na^{22} standard solution to the cotton and dried it under a heat lamp. Since this small amount of solution does not completely wet the cotton, we also added a few drops of water before and after the Na^{22} aliquot. The uneven distribution of cotton in the flask and the heat-lamp drying may affect the distribution of the solution. Therefore we placed the samples reasonably far away from the detector and took the average of four counts, rotating the samples through 90° between counts. We kept counting rates low enough so that dead time corrections were negligible. Despite these precautions the asymmetric distribution still affects the accuracy of the measurements; we found a standard deviation of 2%.

Another problem is the homogeneity of the Na^{22} and Kr^{85} photon sources. Kr^{85} gammas come uniformly from all points in the interior of the container; Na^{22} annihilation photons come from the points where positrons suffer annihilation with electrons. Since the glass walls of the flasks are thick enough to stop all Na^{22} positrons, the worst situation is that in which all positrons stop in the walls and none in the cotton. The error is then less than 0.5%.

Error Assessment in Branching-Ratio Measurement

	Systematic deviation (%)	*Standard deviation* (%)
Na^{22} standardization	1	0.5
Gamma intercomparison	2.5	2.0
Internal gas counting*	1.5	1.3
Total	5.0	2.5
Total error	±7.5%	

* Systematic error includes uncertainties due to remaining slope of differential plateaus and uncertainties in wall effect and counter volumes.

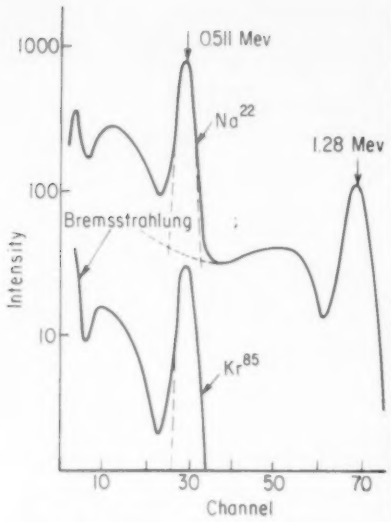

FIG. 2. SCINTILLATION SPECTRA give the intensity of Kr^{85} gamma radiation

Using the procedure given by Campion (4), we standardized the Na^{22} solution by 4π beta-gamma coincidence counting. 90% of the Na^{22} decays by positron emission through the 1.28-Mev level; since the gamma-channel is set to accept only the sum peak from 0.51-Mev and 1.28-Mev photons in coincidence, we got only the absolute positron emission.

Comparison. Figure 2 shows pulse height spectra for Na^{22} and Kr^{85}. For Kr^{85} we established the area under the photopeak by drawing the symmetrical curve in the figure. For Na^{22} the 0.511-Mev peak falls on top of the Compton distribution from the 1.28-Mev line. We got the area of the photopeak by matching a Compton distribution from Co^{60} (gamma-ray energies of 1.17 and 1.32 Mev) to the curve (dotted line) and subtracting. The error introduced by this method does not exceed 2%. In addition, because the 0.511- and 1.28-Mev lines sometimes add up in the scintillation crystal, some of the counts in the 0.511-Mev peak are lost and appear at greater energies; the loss in our geometry was calculated from scintillation-counter efficiencies to be 0.5%. Within the accuracy of the measurement (2%), the energy of the Kr^{85} gamma radiation was the same as that of annihilation radiation. This result supports the most recent energy determination of 0.517-Mev (5).

Beta Measurements

We used internal-gas proportional counting to determine the absolute

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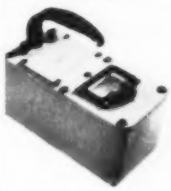

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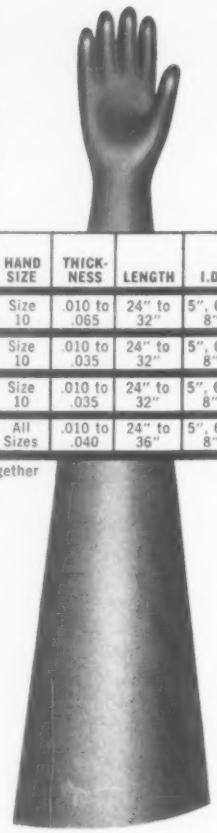

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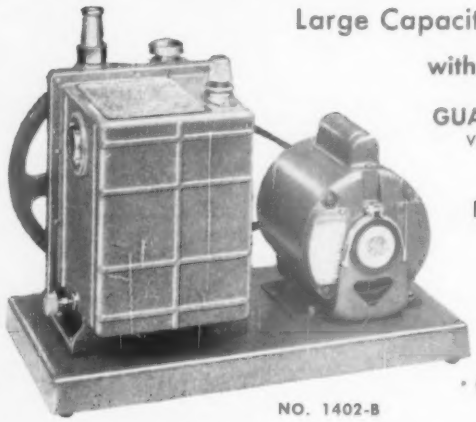

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beta disintegration rates of 14 samples of Kr^{85} taken from the flasks used for the gamma counting. The counter pairs we used had stainless-steel cathodes 2.205 cm in diameter and lengths between guard rings of 19 and 38 cm respectively for the short and long counters (*6*, 7). We found the difference volumes with accuracies to better than 0.3%.

We introduced a sample gas of definite pressure to a pair of counters and added methane to bring the total pressure to 1 atm. By using a non-overloading amplifier with fixed discrimination, we determined voltage plateaus for each counter. After correcting for dead time losses and background we eliminated end-effects by subtracting the plateau for the short counter from that for the long counter. The differential plateaus we got were usually ~300 volts long and had slopes of about 1%/100 volts.

This differential method eliminates end-volume errors only; the other possible source of error is wall losses that occur when beta particles originating near the counter wall are absorbed by the wall without producing ionization in the gas. These losses should be proportional to either $1/SD$ (*7*), where S is the number of primary ions produced per unit path length and D is the counter diameter, or to $1/PD$ (S is proportional to pressure P).

To estimate the wall effect in our experiment we determined the differential counting rate as a function of pressure for the same counter filling of Kr^{85}. We did this by adding methane in steps to the sample in the counters to give total pressures in the range of 0.16–1.0 atm. Figure 3 combines the results of three series of measurements normalized to unit counting rate at 1 atm. Extrapolation to infinite pressure indicates a wall effect of $0.8\% \pm 0.3\%$ for 1 atm.

We could not make an accurate calculation of the wall effect for our counting arrangement for three reasons: first, values of S as a function of electron energy are not available for methane; second, the degree of compensation due to backscattering and secondary electron emission from the wall is uncertain; third, it is not certain that the voltage plateau corresponds to detection of a single ion pair. Nevertheless, assuming that

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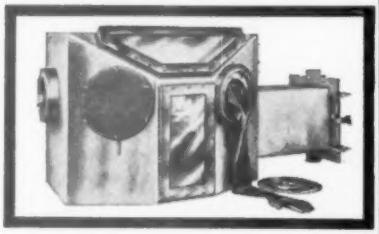

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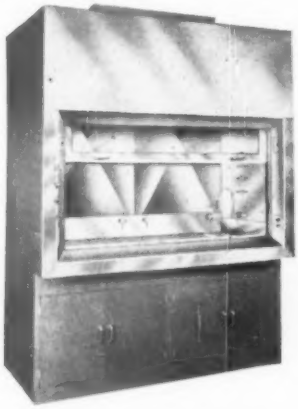

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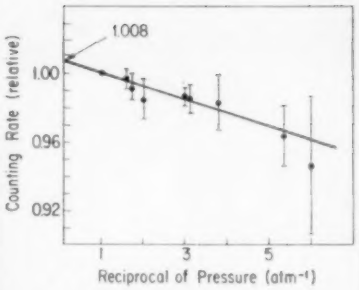

FIG. 3. WALL EFFECT is determined from graph. The error bars allow for slopes of plateaus

the form of $S(E)$ is the same for methane as for air, but smaller by the ratio observed at minimum ionization (*8*), that back-scattering measurements with thin sources in 2π geometry (*9*) include secondary-electron emission, and that single ion pairs are detected, we got ~1% for wall losses. This result is in good agreement with the experiment.

Routine Assay For Kr^{85}

This gamma intercomparison method can be used for routine assays of Kr^{85}. Because only a small fraction of the Kr^{85} disintegrations are followed by gamma rays, Na^{22} standards in the microcurie range are sufficiently intense to be compared with Kr^{85} sources in the millicurie range—a range that is probably most frequently encountered in routine assay. These activities allow the distance from the scintillation crystal to be larger than that for the branching-ratio measurement in which the activity that can be handled in the gas-counting apparatus is limited. Thus sample asymmetries are less significant.

The accuracy of the Kr^{85} assay is essentially determined by the uncertainty in the branching ratio; the remaining errors, such as counting statistics and differences in absorption within sample and container walls, can be kept much lower.

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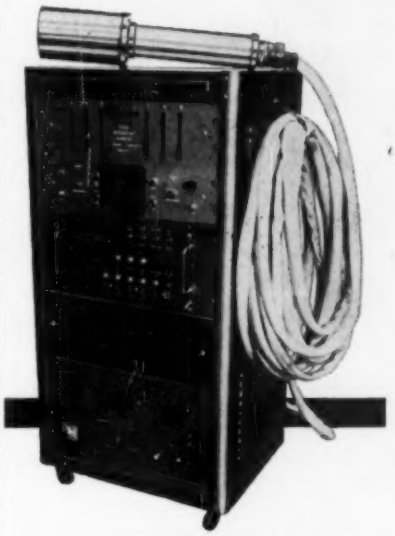

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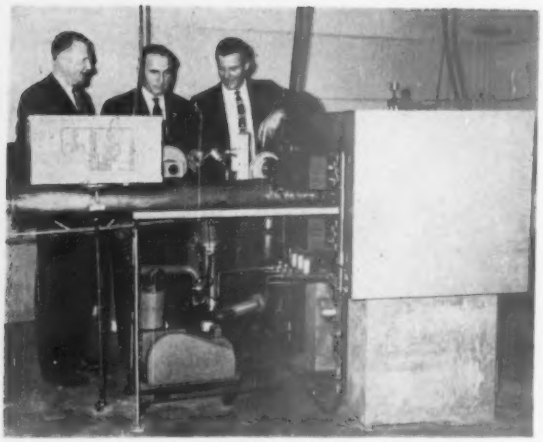

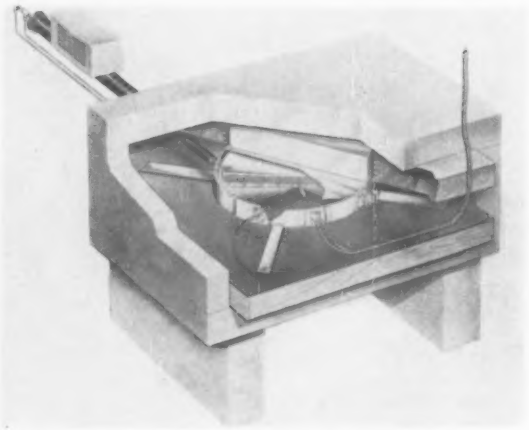

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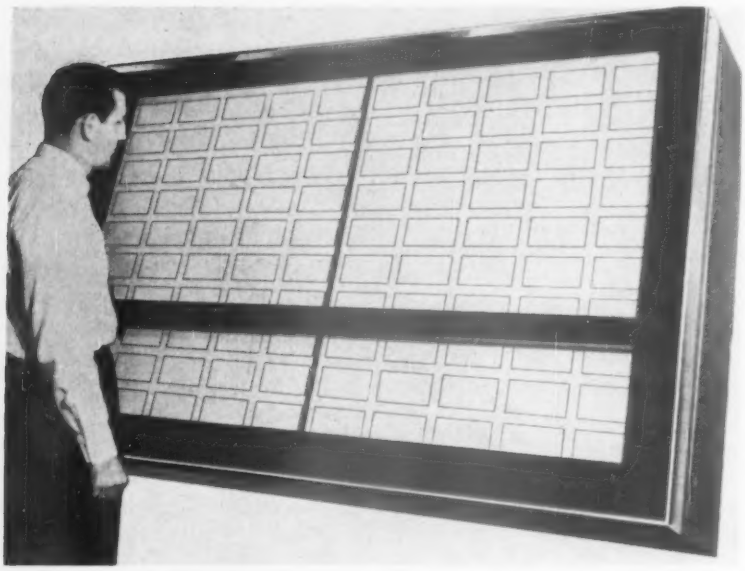


Recorder and Annunciator Accommodates 400 Tracks

K-Logger (above) makes 10–400 analog recordings at rates up to 10 points per sec on a large sheet of paper with a series of 4 × 6-in. or 3 × 6-in. chart frames. Recordings are made by a print bar that scans up and down on the sheet, printing one point in up to four colors in each frame per scan. Since the time scale is the same on all chart frames one can easily cross-correlate. The recorder contains a built-in annunciator.—Keinath Instrument Co., 1223 Grandview Ave., Columbus, Ohio.

Plastic Scintillators

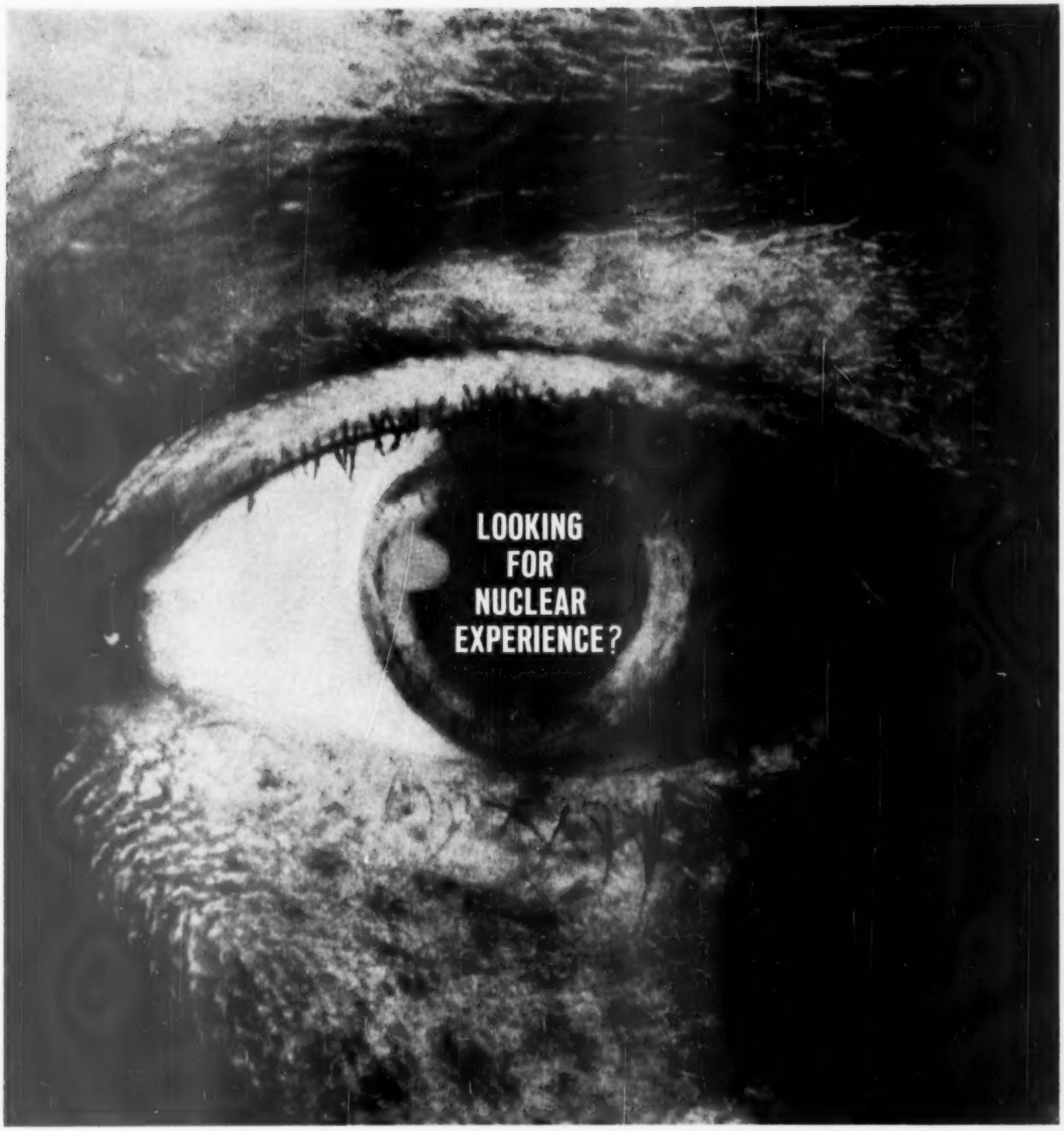
Three types of plastic scintillators with peak emissions at 4200, 4350 and 4500 A come in cylinders or slabs. Fluors are polystyrene-based with pulse height that is 60% of anthracene decay constant of 3×10^{-9} sec, density of 1.07 gm/cm³ and refractive index of 1.59.—Allied Research Associates, Inc., 43 Leon St., Boston, Mass.

Low-Radioactivity Glass

A new kind of glass with radioactivity of <10 cpm/kg has thermal coefficient of expansion of $\sim 95 \times 10^{-7}$ per °C. The glass will be used in photomultiplier tubes.—Corning Glass Works, Corning, N. Y.

Beta-Detection System

Lowbeta, a low-background counting system, keeps background interference to less than 0.25 cpm for a 1-in.-dia. detector. Detectors from ½ to 3 in. are available. Shield is 18 in. square and weighs 1,500 lb. System also has transistor electronics, plug-in



Examine Vitro's record of engineering services. Nuclear power plants: 626 MWE ■ research and test reactors: 321 MWT ■ shielded hot cells: 8.2 x 10^6 curies capacity ■ chemical separations facilities: over 2000 tons per year throughput. Also included are laboratories, test devices and isotopes separations plants. Completed Vitro nuclear projects are worth more than 1.5 billion dollars.

Vitro

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printed circuit cards, illuminated programming panel, preset-time and count control and simultaneous alpha and beta counting with four channels of readout and two detectors.—Sharp Laboratories, Inc., Box 1302, LaJolla, Calif.

Remote Positioner

Rotolift (above), a stainless-steel remote-positioning unit that holds several pieces of apparatus simultaneously, has a platform that rotates in either direction. Standard unit weighs 14 lb and is 26 in. high with a 9-in. base.—Nuclear-Ohio, Inc., 27105 Knickerbocker Rd., Bay Village, Ohio.

Cobalt Units

Five cobalt-60 radiography cameras that are designed primarily for panoramic or internal radiography, have capacities of 1, 5, 10, 30 and 100 curies of cobalt-60. The machines range from 190 to 1,100 lb. All units can use more than one radioactive source.—Radionics Inc., Lafayette and Water St., Norristown, Pa.

Stainless Steel for NPR

Over 200 miles of tubing will go into the 10 heat exchangers that Combustion Engineering is building at the New Production Reactor at Hanford. The tubes, 49–54 ft long, are made from stainless steel strips 3.8 in. wide and are annealed and redrawn several times to give wall thicknesses of 0.049 in. and diameters of ⅝ in.—Allegheny Ludlum Steel Corp., Oliver Bldg., Pittsburgh 22, Pa.

Neutron Shielding Material

Delka Radiation Barrier contains a large percentage of high-density polyethylene that acts as an effective neutron-shielding agent. Barrier coatings can be applied by spray or brush, made into foams or ground into powder to be mixed with fillers for building materials.—Delka Research Corp., Martial & Co., Inc., 29 E. 61st St., New York 21, N. Y.

Millimicrosecond Pulser

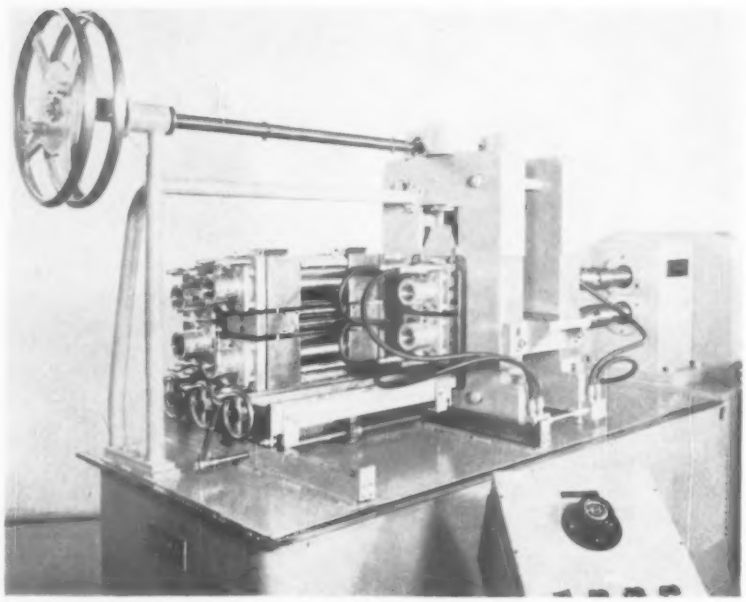
New millimicrosecond pulse source delivers positive and negative pulses simultaneously and is operable in any position because it uses no mercury switches. The new instrument offers fast rise time: 0.5 mμsec, 2–100-mμsec duration, large repetition-rate range: 10–100,000 pps and single-shot capability. Pulse amplitudes are fixed at ~8 volts into 50 ohms.—Reach, McClinton and Humphrey, Inc., 1235 Statler Bldg., Boston 16, Mass.

Spectrometry Standards

Six low-cost, calibrated reference standards for gamma spectrometry come in 1.25-in.-dia plastic disks or 5 × ⅝-in. plastic cylinders (for standard well-type detectors). The six isotopes (Co^{57}, Ce^{137}, Mg^{54}, Na^{22}, Co^{60}, Ba^{133}) have principal gamma photopeaks with ranges from 122 kev to 1.33 Mev. Well sources contain 0.03–0.1 μc and the disk type 1–2 μc.—New England Nuclear Corp., 575 Albany St., Boston 18, Mass.

Transistor Survey Meters

New 5-oz. transistorized G-M counter, no bigger than a pack of cigarettes, operates on penlight cells. Having an energy response of 30 kev-2 Mev, it crackles at 1 mr/hr and whistles at

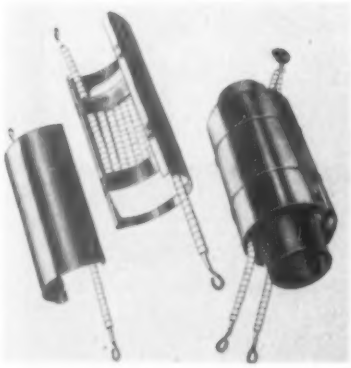


Plutonium Rolling Mill Adapts to Glove Box

2-high/4-high combination rolling mill (above) can be enclosed in a controlled-atmosphere glove box for processing alpha-active pyrophoric materials like plutonium. Machine operates in either a 6 × 8-in. 2-high setup or a 1½-in. and 6 × 8-in. 4-high setup. 2-high setup is used for hot or cold breakdown rolling. Grooved rolls process rounds from 1 to ¼-in. diameter. In 4-high setup, strip is cold-finish-rolled to 0.002-in. gages.—Loma Machine Co., Inc., 114 E. 32nd St., New York 16, N. Y.

100 mr/hr. The system has a life of 5×10^{10} counts minimum.

Survey meter, which operates on 2 standard flashlight batteries, measures alpha, beta and gamma radiation. It is stabilized for changes in voltage and temperature (works from −22° F to 125° F with 15% accuracy). Meter has a built-in loudspeaker and earphones. Two ranges can be selected with a toggle switch: 0–10 and 0–200 mr/hr.—Gelman Instrument Co., 106 N. Main St., Chelsea, Mich.



Clamp-on Heaters

Two kinds of clamp-on units (above), NV-C unit and Class 712, are used for stress-relieving welds at the Indian Point Atomic Power Plant. Units, which clamp over the pipe and around the weld, can be used where working space is restricted. NV-C unit is a low-voltage, high-current heater for pipes or tubes from 2 to 6 in. and with wall thicknesses of $\frac{3}{8}$ in. Model Class 712 is a clamp-on type of heater for higher voltages in stress-relieving welds for pipe from 1 to $2\frac{3}{4}$ in. It operates from a 220-v source with current supplied through a regulating unit with six 12-step circuits that treat 6 welds at temperatures to 1,375° F.—Electric Arc, Inc., 152 Jelliff Ave., Newark 8, N. J.

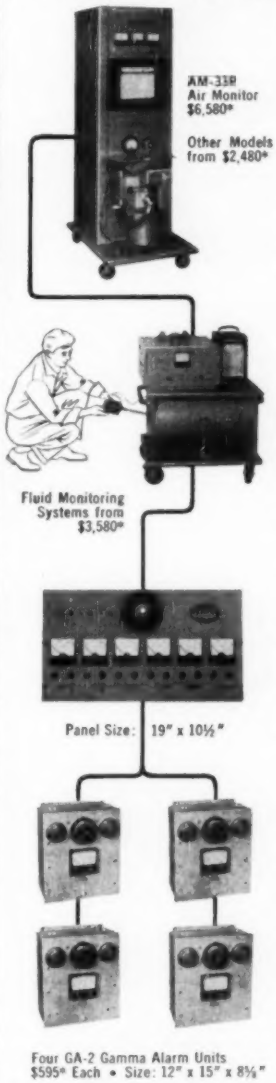
New Decade Scaler

Hamner N-240 Decade Scaler, designed for analytical scintillation and proportional counting systems, uses 4 plug-in decade strips and a 4-digit electromechanical register. The scaler operates in manual, preset-time or preset-count modes. Pulse-pair resolution is 1 μsec with a possible continuous repetition rate of 250,000 cps.—Hamner Electronics Co., Inc., P. O. Box 531, Princeton, N. J.

Monitoring Systems

DESIGNED, BUILT AND BACKED BY NMC INDIANAPOLIS, INDIANA

What is your radiation monitoring problem? Airborne particulates . . . gaseous or liquid radiation . . . or gamma area radiation? NMC equipment can monitor any one or all with individual units or complete systems. The system shown here presents data at each station and on a control room follow meter panel. It warns of caution and alarm levels; can even operate emergency controls.



AIR MONITORS

NMC air monitors offer many exclusive advantages. For example, Model AM-33R shown here detects and identifies long half-life emitters directly, almost immediately, with one detector. Other monitors require five hours or more for identification, due to the natural radon progeny. The four NMC models are . . .

MODEL	CHANNELS	FILTERS	ACTIVITY DETECTED
AM-2A	1	Fixed	α, $\beta\gamma$ or γ
AM-3A	1	Moving	α, $\beta\gamma$ or γ
AM-22R	3	Fixed	α and $\beta\gamma$ Shows ratio of $\beta\gamma/\alpha$
AM-33R	3	Moving	α and $\beta\gamma$ Shows ratio of $\beta\gamma/\alpha$

FLUID MONITORS

The NMC fluid monitoring system detects radioactivity in gas or water at MAC levels. Used with an NMC air monitor, it measures activity of the gaseous component of the discharge from the air monitor. Contamination and a separate pumping system are eliminated by employing the air pumping system and filter mechanism of the air monitor. The fluid system includes the FMS-1 shield with 30 liter sampling chamber, and two detectors—GM or NaI scintillation—operating in parallel; the LCRM-2M logarithmic count ratemeter with built-in bell and alarm lights; and portable EA graphic recorder.

FOLLOW METER PANELS

Each monitoring station can be connected to a follow meter panel in the central control room with inexpensive unshielded standard electric code wiring. There's a meter for each station to show the radioactivity being detected, and lights to indicate caution and alarm levels. The bell sounds for an alarm condition at any station. Multipoint recorders and remote emergency controls may be connected to the panel.

AREA MONITORS

Each of the four GA-2 units shown here is a complete monitoring station that indicates and reports unusual or excessive gamma radiation. It mounts on the wall and wires to any 110-volt circuit, eliminating the central power supply required by other systems. Each GA-2 has an amber and red light, bell, indicating meter, and complete alarm system. Units readily adapt to a complete system. They connect to follow meters and graphic recorders; are interchangeable without the usual installation matching and calibration. They are not sensitive to temperature, line voltage changes or external electro-magnetic radiation. The amber light is also a fail-save device, signaling component failure. An auxiliary power supply for each GA-2 is available.

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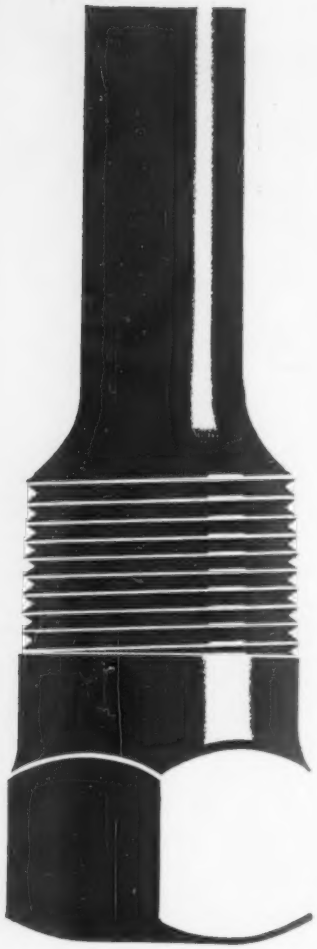

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Products and Materials

Department starts on page 102

Shielding Material

Lignostone (BF 2/1 w.v.) (above) is a fast-neutron shielding material now being used at Britain's Hinkley Point Power Station. Made from 0.04-in.-thick veneers of beechwood, it is cross-bonded with ~19% phenolformaldehyde and has a 1.30–1.38 specific gravity. For added shielding protection Lignostone comes with 30–150 mg/cm² B^4C inserted in layers before bonding. Lignostone comes in 35½ × 35½-in. sheets with thicknesses from $\frac{5}{16}$ to 4¾ in. thick, or 37½ × 55-in. sheets $\frac{5}{16}$–4-in. thick.—Lignostone Dept., Techno Exports, P. O. Box 65, Gracie Station, New York 28, N. Y.

Read-o-matic Computer Scaler

Model QS-6 scaler and events-per-unit-time meter computes count rate or frequency automatically. Data is also available for readout on a paper-tape printer. Single or repeat-cycle counting is provided with adjustable delay times between cycles for visual or paper-tape readout. Instrument also reads ratios of unknown counting rate to standard count rate.—Atomation Inc., 5959 S. Hoover St., Los Angeles 44, Calif.

LITERATURE AVAILABLE

High-Density Concrete Products. 8 pp.; Ray Proof Corp., Stamford, Conn.

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Fast-Neutron Monitor. 2 pp.; Burndept Ltd., Erith, Kent, England.

Ionization-Gage Controls. 2 pp.; F. J. Stokes Corp., 5500 Tabor Rd., Philadelphia 20, Penna.

Milli-Microvoltmeter and Multi-Range Electrometer. 4 pp.; Keithley Instruments, Inc., Cleveland 6, Ohio.

Servo Amplifier and Motor. 2 pp.; Thermo Electric Co., Inc., Saddle Brook, N. J.

Process Control. 10 pp.; Bailey Meters & Controls Ltd., Purley Way, London, England.

Differential Data Acquisition Systems. 4 pp.; Electro Instruments, Inc., 3540 Aero Court, San Diego 11, Calif.

Spectrographic Supplies. 24 pp.; Jarrell-Ash Co., 26 Farwell St., Newtonville, Mass.

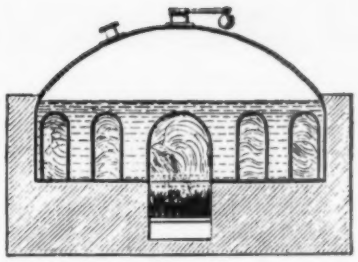
Why Do You Need Reference Sources? 4 pp.; Picker X-Ray Corp., 25 South Broadway, White Plains, N. Y.

New Instrumentation for Nuclear Research. Bulletin 172, 4 pp.;
Scintillation Detectors. Bulletin 179, 2 pp.; Technical Assoc., 140 W. Providencia Ave., Burbank, Calif.

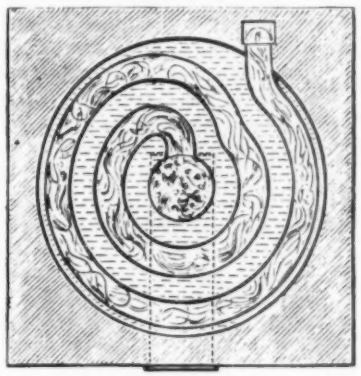
Hydraulic (Oil) Cylinders. Bulletin 113-B, 8 pp.;
Air Motor. Bulletin 215, 8 pp.;
Air Power Cylinders. Bulletin 213-B, 16 pp.; Hannifin Co., Des Plaines, Ill.

Thermocouples and M_xO Thermocouple Wire. 4 pp.; Barber-Colman Co., Wheelco Instr. Div., Rockford, Ill.

Three Detectors for α, β-γ, n Radiation. 4 pp.; Eberline Instr. Corp., P. O. Box 279, Santa Fe, N. M.



CROSS-SECTIONAL VIEW—SIDE



CROSS-SECTIONAL VIEW—TOP

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No known record exists today naming the inventor of this cylindrical boiler with a spiral flue used in 1780, but the design indicates a mind willing to push beyond accepted practices of his day. Flame entered the center of the boiler and moved through a spiral flue to the chimney. This relatively long traverse of the flame permitted the water to absorb a great deal of the heat, improving the efficiency of this early steam generating system.

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INDUSTRY NOTES

● AEC spent a total of $717-million in fiscal 1960, or $10.19/lb, an average of 13¢/lb less than last year, for uranium oxide. Moreover, this represents a balancing of foreign-produced U_3O_8 costs, which increased from $11.84 to $12.01/lb, and domestic costs, which dropped 41 cents from $9.40 to $8.99/lb. Mills averaged $8.78/lb delivered, down from $9.18 in fiscal 1959. Higher foreign costs resulted from increased costs of production abroad and foreign-exchange factors, particularly for Canadian ore, up 17 cents/lb to $11.04. Lower domestic costs resulted after new contracts were merged with those expiring March, 1962. Total U_3O_8 purchased increased 9%, with foreign purchases remaining about the same. All AEC commitments on domestic U expire Dec. 1966.

● **ASTRA Inc.**, Raleigh, N. C., has been retained as consultant on radiation shielding for space vehicles by the Astronautics div. of Chance Vought. The Convair, Fort Worth, div. of General Dynamics Corp. has hired ASTRA for experimental work in producing ultra-high-velocity particles similar to those existing in space.

EXPANSIONS. A $3.2-million research and development center will be built by late 1961 by the **Pfaudler Permutit Inc., Pfaudler Co.** div. in Henrietta, N. Y. The 40,000 square feet of additional space will provide facilities for over 100 scientists, engineers and technicians for research in three major fields: ceramics, metallurgy and organic chemistry. . . . **Douglas Aircraft Co.** has formed a subsidiary corporation, **Astropower, Inc.**, for research into exotic nuclear, chemical and electrical propulsion systems for space vehicles including specialized high energy systems. . . . **Fenn Manufacturing Co.**, Newington, Conn., plans to add 150,000 square feet of manufacturing area to its main plant to be used for production among other things of precision-metal-forming machinery and nuclear components. . . . A new department under Pincus Peyser has been opened by **New England Nuclear Corp.** to specialize in biochemical synthesis of labeled compounds. . . . **Varian Associates**, Palo Alto, Calif., has established a department under Norman Hiestand to study and develop military applications of magnetometry. Initial research and development revolve around Varian's two proprietary magnetometer types: the proton free-precession and alkali vapor.

NEW BUSINESS. The U. S. Signal Corps awarded **Nuclear Corp. of America** a contract for a gamma-ray "pin-hole" camera capable of nuclear radiation detection and a televisual system to be used for viewing the distribution of radioactive sources. . . . AEC awarded Aerojet General's **Aetron div.** a $7-8-million contract to handle architect-engineering for a Project Rover nuclear-engine test cell at Jackass Flats, Nev. The test stand for down-firing will be built mainly of aluminum alloys rather than structural steel.

NEW COMPANIES. Magnion, Inc., Cambridge, Mass., has been established by one-time president and founder of Tracerlab, Inc., William E. Barbour, Jr. Research and development of magnetic systems and products will be applied in the fields of plasma and thermonuclear studies, nuclear research, magnetobiology and magnetochemistry investigations and generation of very high magnetic fluxes for both industry and science . . . **Servonuclear Corp.**, Long Island City, N. Y., has been formed by Alex Meshbane, a former sales engineer at Baird-Atomic, and Anthony Serao, formerly New York service manager for Nuclear-Chicago.

FINANCE. Brush Beryllium Co., Cleveland, Ohio, had total sales for the first nine months of 1960 amounting to $20,897,338, up from $13,583,304 for the same period in 1959. Net income was $1,511,100, or 80 cents/share, up from 69 cents/share in 1959. . . . **Royal Industries, Inc.**, Los Angeles, Calif., reported net earnings in October of $173,042 for the three-month period ending Sept. 30, equal to 15 cents/share on 1,118,488 shares outstanding. Consolidated net sales for this period were $4,444,950; sales for the nine months were reported at $10,554,636, with net earnings through the third quarter of $313,181, or 28 cents/share.

NEWSMAKERS

Robert C. Thorburn was named manager of the General Electric Vallecitos Atomic Laboratory's newly formed Nuclear Safety subsection. His duties include responsibility for nuclear safety for the entire Atomic Power Equipment dept.

Raymond W. Durante has been appointed to head the Washington office of Aerojet-General Nucleonics as technical representative. During 10 years in the nuclear energy field he's been manager of nuclear sales for Allis-Chalmers' Washington dept. and supervisor of nuclear engineering sales for the American Machine and Foundry Co., as well as project engineer on the Savannah River project.

Durante

Henry B. Hansteen, professor of the Department of Electrical Engineering at City College, N. Y., has taken a leave of absence to head the fellowship activities of the International Atomic Energy Agency in Vienna.

John V. Vinciguerra has been named director of AEC's office of contract policy to succeed **John R. Moore,** who transferred to the Commission's Oak Ridge Operations office as assistant manager for administration. Vinciguerra was assistant director for safeguards, Division of International Affairs, and has been a member of the AEC staff since 1947.

Two regional managers have been appointed by Charles Walsh Associates, Inc., manufacturers' representatives of Deerfield, Ill., to head the eastern office: **Robert W. Lichtinger,** formerly a Midwestern sales representative for Radiation Instrument Development Laboratory; for the Southern office, **Joseph D. Eddlemon,** formerly of Oak Ridge National Laboratory. Walsh represents a number of nuclear industries.

The United Kingdom Atomic Energy Authority has announced senior appointments to its development and engineering group. **R. V. Moore,** formerly director of reactor design, and **Hans Kronberger,** formerly director of research and development, have been appointed deputy managing directors for projects and development, respectively. **Paul T. Fletcher** will be deputy managing director of the group for general management; **S. Fawcett,** formerly deputy director, succeeds Moore; **Harold K. Hardy** will be director of fuel-element development, and **Frederick W. Fenning,** director of research technology.

New England Nuclear Corp. has appointed **Paul A. McNulty** sales manager, a new post created to keep step with increased sales.

Erwin Tomash, president of Telemeter Magnetics, Inc., and **Richard Bellman,** senior mathematician at Rand Corp., have been elected to the board of directors of Solid State Radiations, Inc., Culver City, Calif. SSR is developing semiconductor radiation detectors and conducting research and development in nucleonics, semiconductors, electronics and data handling.

Vitro Corp. of America has appointed **Wayne P. Brobeck** director of customer relations for its Washington office. Brobeck, formerly of Ionics, Inc., was assistant executive secretary to the Joint Congressional Committee on Atomic Energy from 1947 to 1957. Vitro's Washington staff includes Adm. A. G. Noble (ret.), vice-president, and Edward G. Littel, assistant to the president.

Brobeck

Lloyd V. Berkner, president of Associated Universities, Inc., operators of Brookhaven National Laboratory, has been elected president of the Institute of Radio Engineers for 1961. He succeeds **Ronald L. McFarlan.**

Joseph R. Feldmeier, formerly at Bettis Atomic Power div. of Westinghouse Electric Corp., has been appointed associate director of research of Philco Corp.'s research div.

Eugene J. Ziurys has joined Thompson Ramo Wooldridge Inc. as

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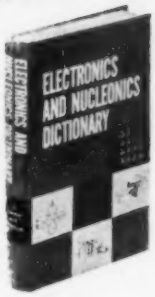

Just Published. Here are definitions of over 13,000 terms—accurately and clearly defined, ranging from television to avionics, from nuclear engineering to space electronics. Labels synonyms, deprecated terms, and obsolete terms—covers spelling, hyphenation, and abbreviations. By Nelson M. Cooke, Cooke Eng. Co.; and John Markus, McGraw-Hill Book Co. Over 13,000 terms, 452 illus. and diagrams. $12.00

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Brings together the essential facts on problems of radiation and its control. Gives technical data and practical methods needed to control the environment of workers, equipment, and materials—and also keep the public safe from the damaging effects of radiation. This book equips you to deal safely with radiation regardless of your background in the field. It provides a vast array of information on exposure standards, sources of radiation, waste disposal, air and water pollution control, physiological effects of radiation, tables, general data, helpful glossary, etc. Edited by Hanson Blatz, Radiation Consultant, City of N. Y. 269 illus., 213 tables, $27.50

PROPULSION SYSTEMS for SPACE FLIGHT

Here is a comprehensive view of the design, development, and operation of reaction engines for use in outer space. The book surveys the entire field from turbojets to photon-propulsion, stressing the more advanced types of engines. In addition, it describes modern developments in ion propulsion, plasma drives, nuclear propulsion, chemical rockets, and other important areas of research. The book also provides a realistic picture of the space environment in which such craft will travel and the problems which must be overcome. By William R. Corliss, The Martin Company. 312 pp., 149 illus., $10.00

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consulting engineer in the preliminary design department of the Tapco Group's New Devices Laboratory. He was formerly with the General Electric Co.'s Aircraft Nuclear Propulsion Laboratory as principal engineer for advanced design.

Herbert Lawrence, Jr., has been appointed to the nationwide sales dept. of Victoreen Instrument Co. He will be in charge of the company's nuclear-spectrometry products and specialize in market development and sales of a new multichannel analyzer that Victoreen says is of "extremely advanced design." Lawrence was formerly regional field sales engineer for Marion Instrument div. of Minneapolis-Honeywell.

Thayer

Robert L. Junkins, formerly senior engineer, radiological evaluation, at Hanford Laboratories' Radiation Protection Operation, has been appointed consulting radiological scientist in the Programming Operation at Hanford.

Harold E. Thayer has been elected president of the Mallinckrodt Chemical works, St. Louis, Mo., to succeed retiring president, **Joseph Fistere.** Thayer joined Mallinckrodt in 1939 as a member of the sales department. He was project manager of the Uranium div. in 1943, was appointed a vice-president of the company in 1950 and was in charge of the AEC's Weldon Spring project for Mallinckrodt. **Charles D. Harrington** and **Frederick M. Belmore** were elected vice-presidents; Harrington, who received recently the 1960 Midwest Award of the American Chemical Society's St. Louis section for his work on uranium metal, is general manager of the company's Nuclear div.; Belmore is general manager of the company's Industrial Chemical div.

Lawrence

NUCLEAR CALENDAR

Jan. 8–12—Symposium on Thermoelectric Energy Conversion (*Statler Hotel*), Dallas, Texas. Contact: Philip Klein, General Electric Co., Syracuse, N. Y.

Jan. 16–17—Symposium on Space Instrumentation, Washington, D. C. Sponsors: Professional Group on Space, Electronics and Telemetry of the Institute of Radio Engineers. Contact: H. B. Riblet, Applied Physics Lab., The Johns Hopkins Univ., Silver Spring, Md.

Jan. 16–19—Instrument Society of America Winter Instrument-Automation Conference & Exhibit (*Jefferson Hotel*), St. Louis. Contact: William H. Kushnick, Executive Director, ISA, 313 Sixth Ave., Pittsburgh 22, Pa.

Jan. 25–27—Southern California Industrial Radioisotopes Symposium, Los Angeles. Sponsored jointly by Western Gear Corp., Northrup Corp. and California governmental, university and professional organizations in cooperation with AEC. Contact: Edward W. McCauley, Systems Management div., Western Gear Corp., P.O. Box 182, Lynwood, Calif.

Feb. 16–17—Symposium on Materials for Nuclear Application (*Student Union Building*), University of New Mexico, Albuquerque. Sponsor: American Society for Metals (Albuquerque and Los Alamos Chapters), and the University of New Mexico. Contact: A. W. Snyder, Radiation Effects div. (5432), Sandia Corp., Albuquerque, New Mexico.

Feb. 26–March 1—Pacific Electronic Trade Show, Los Angeles (*Great Western Exhibit Center*). Contact: Pacific Electronic Trade Show, 2216 South Hill St., Los Angeles 7, Calif.

March 5–9—Sixth Annual Gas Turbine Conference and Product Show (*Shoreham Hotel*), Washington, D. C. Sponsors: Gas Turbine div. of the American Society of Mechanical Engineers and the U. S. Department of Defense. Contact: ASME, Meetings dept., 29 West 39th St., New York 18, N. Y.

March 21–23—Annual American Power Conference (*Sherman Hotel*), Chicago. Sponsors: The American Society of Mechanical Engineers, Western Society of Engineers, National Association of Power Engineers, American Institute of Electrical Engineers, etc. Contact: Director R. A. Budenholzer, Illinois Institute of Technology, 35 West 33rd St., Chicago 16, Ill.

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During the 9-year span of effort, General Electric engineers and scientists have achieved major breakthroughs in reactor technology, shielding techniques, high temperature resistant materials, specialized controls capable of functioning reliably in a high density radiation environment, and in other areas.

One of these technical achievements is discussed to the right in capsule article form. In succeeding announcements other interesting technical advances at the Aircraft Nuclear Propulsion Dept. of General Electric will be discussed.

ADVANCES IN NUCLEAR SHIELDING TECHNIQUES

As the shield is the largest weight item in the propulsion system, major effort has been applied to shield theory, experiment and design since the initiation of the Aircraft Nuclear Propulsion program.

The dimensions of the problem faced are evident when you consider that General Electric engineers had to find a way to reduce shielding weights from hundreds and thousands of tons for stationary nuclear power plants by orders of magnitude.

One of the major gains registered was the concept of the divided shield, i.e. dividing the shielding between the power plant and the crew compartment. This concept takes advantage of the fact that even the most sensitive component of the system can withstand 10,000 times the amount of nuclear radiation that a human being can tolerate.

This concept has been defined through the use of improved analytical techniques to produce detailed radiation patterns around reactor shield assemblies. New computer programs, and new calculation techniques developed at General Electric have yielded invaluable data for the design of sophisticated shielding configurations.

Additional improvements have been attained through study of materials. Materials not formerly employed for reactor use have been developed and applied. Design techniques have been created which take maximum advantage of these materials.

These theoretical and experimental investigations have resulted in shields which are so light that nuclear aircraft need be no heavier than present day airplanes. Shielding weight is no longer a critical problem.

Although much has been accomplished, further improvements in shielding technology are being developed through improved calculation methods, advanced materials development and more sophisticated structural design.

Opportunities exist today for Engineers and Scientists from many disciplines to contribute to precise solutions of a variety of sophisticated problems pertaining to the final development stage of General Electric's nuclear propulsion system for high performance aircraft.

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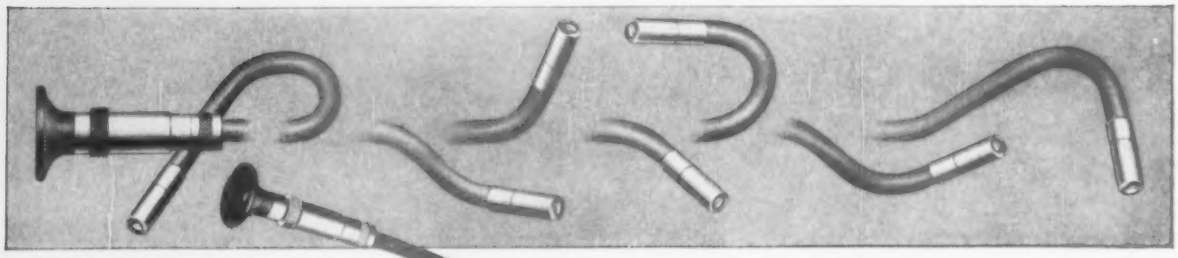

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Lockheed Nuclear Products designed and built the portable pool-type reactor for the Atomic Energy Commission's "Atoms at Work" exhibition, which is now touring South America. A 10-kw training reactor has just been completed for Ohio State University. And, for critical experiments which the National Aeronautics and Space Administration is conducting at Plum Brook, LNP is building a low-power reactor and a cyrogenic test loop.

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A letter, wire, or phone call will bring a Lockheed Nuclear Products representative to your plant or office to discuss your problems in:

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Write: Nuclear Sales Manager, 1500 Northside Drive N.W., Atlanta 18, Georgia.

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